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Propulsion and Auxiliary Systems Department
Progress Report

Evaluation of an Inclined Mounting System for Diesel Engines

by

Donald Thomson

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DTRC/PAS-88/31 Evaluation of an Inclined Mounting System for Diesel Engines

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ABSTRACT

The diesel engine in a 40-foot test craft was installed on an inclined mounting system in an effort aimed at reducing sound levels aboard craft. An evaluation of the vibration levels and sound levels in the boat cabins indicated that the mounting system was very effective to the degree that airborne sound transmission and propeller induced noise now control the acoustical environment.

ADMINISTRATIVE INFORMATION

This work was authorized by the Naval Sea Systems Command, PMS 300, in accordance with SEATASK 3008-8403 of 24 Nov 1987 and performed by Code 2744 of David Taylor Research Center.

INTRODUCTION

This report discusses progress in a task directed toward the development of techniques for reducing sound levels aboard U. S. Navy craft. Recently acquired craft continue to exhibit high A-weighted sound levels in excess of 84 dB, the maximum level allowed without hearing protectors, assuming 8 hours exposure per day*. Diagnostic tests conducted on new 40-foot Personnel Boats MK 4 indicated that vibration from the engine and propeller caused high levels of radiated sound from the boat structure. The vibratory energy flanks bulkhead acoustical treatments and radiates acoustical energy from various cabin surfaces.

* OPNAVINST 5100.23B of 31 Aug 1983

High vibration levels have been experienced even though engines are installed on vibration isolation mounts and the propeller is located with considerable clearance between the propeller tip and hull. Vibration isolation mounts typically used on U. S. Navy craft have been evaluated* in bench tests in the Mount Test Facility at the Annapolis Laboratory. These mounts were found to have considerably higher natural frequencies than advertised which leads to greater transmitted vibration.

TASK APPROACH

It was decided to investigate a focal point mounting system wherein the axis of the mounts is tilted inward instead of oriented vertically as in base-mounted systems. In a focal point mounting system the mounts are selected and arranged in relation to the roll axis, the axis of minimum inertia. This practice has been extensively followed in automotive applications. When correctly designed a focal point mounting system yields low natural frequencies for all six degrees of freedom. Forces transmitted to the boat structure are much less in a focal point mounting system than with a base-mounted system; reduced forces equates to reduced noise levels. A discussion of the inclined mounting system design is presented in Appendix A.

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* DTNSRDC ltr 9073, Code 2744DCT of 8 Jun 1987

DESCRIPTION OF TEST CRAFT

A 40-foot Personnel Boat MK 4 built by Triumph Boatbuilders circa 1968 was acquired for use in investigating noise reduction of craft. The boat has been reconditioned and brought up to operational status with the installation of a Detroit Diesel model 6-71N engine which was hard mounted. The Allison reverse/reduction transmission has a gear ratio of 1.52:1 and drives a Columbian Bronze 3-blade propeller of 24-in. diameter and 19-in. pitch. Tip clearance is 4½-in. as installed. An inboard profile of the boat is shown in Fig. 1.

In preparation for the upcoming noise level investigations a baseline acoustical treatment was installed in the engine compartment. This consisted of attaching ½-in. plywood to the overhead of the engine compartment, except hatches, as indicated in Fig. 2. Acoustically lined plywood ducts, port and starboard, were attached to the overhead to attenuate sound escaping from the engine compartment via the air intake openings. The bulkheads were covered with ½-in. plywood spaced out from the bulkhead by wood strips resulting in a 1-in. airspace. The plywood had large rectangular cutouts generally near the middle of the bulkheads. The periphery of the openings was covered with "Scotchmate" hook and loop type fasteners, a product of the 3M Company. Acoustical blankets consisting of mass-loaded vinyl sheets with 1-in. thick fibrous glass insulation under a glass cloth facing were procured and attached over the large openings. The hook and loop fastening system allowed the blankets to be easily attached or removed from the bulkhead for diagnosing and evaluating noise reduction treatments.

Fig. 3 shows a "close-coupled" engine enclosure that was used as an additional noise evaluation technique. This consisted of an aluminum framework attached between the engine compartment deck and the overhead to which acoustical blankets were attached using hook and loop fasteners. Figs. 4 and 5 show the engine enclosure and a 3-piece secondary hatch cover, respectively. Not shown is another acoustically lined air intake duct connected to the enclosure. Treatment in the form of closed-cellular foam pads covered with mass-loaded vinyl was attached to the forward and aft bulkheads below deck level which, in effect, extended the treatment to the hull. Finally all miscellaneous holes in the bulkheads were plugged. The forward and aft cabins were acoustically hard spaces; there were no seat cushions and no sound absorbing material on the overhead or deck; cabin bulkheads were bare.

Engine exhaust noise was reduced by use of a Maxim model "MO" silencer through which most of the raw cooling water was delivered for added effectiveness. The silencer was mounted transversely aft of the engine so that any possible shell noise would be contained in the engine compartment.

TEST PROCEDURE

The craft was initially operated to acquire base-line noise levels. Maximum engine speed attainable was approximately 2200

RPM; a standard test speed of 2100 RPM was therefore selected. The acoustical evaluation consisted of recording sound and vibration levels at many locations throughout the craft as shown in Fig. 1. Vibration levels were obtained from Endevco model 2217E accelerometers, conditioned with Ithaco model 125L or model 143L preamplifiers, and recorded on a Lockhead "Store 4" magnetic tape recorder. Sound levels were recorded from Genrad ½-in. electret-condenser microphones coupled to Genrad type 1560-P42 preamplifiers.

MOUNTING SYSTEM DESCRIPTION

The next major effort was the installation of the inclined mounting system. Fig. 6 shows the engine mounting frame weldment which was fabricated of aluminum alloy and weighed 128 lbs. Fig. 7 shows a trial installation of the engine on the frame. Scale drawings in Figs. 8 and 9 show the method by which the mounting cradle was joined to the isolation mounts at the forward and aft mounts, respectively. It is shown that the arms from the cradle were designed to pass through the longitudinals; reinforcement was accomplished by an aluminum cap port and starboard, that extended nearly the full length of the engine compartment. The mounts were carried on transverse plates tied into the inboard and outboard longitudinals. This was done to prevent twisting of the longitudinals that typically occurs with mounting brackets to create a high-impedance foundation. The forward-port mount is shown in Fig. 10. The bar shown across the top of the mount was used only to preload the mounts to achieve bolt hole alignment during assembly; the bars were removed after engine installation.

The soft mounting system necessitated the use of two flexible couplings spaced a suitable distance apart and connected by a floating shaft. No single coupling was found that would be capable of transmitting the torque with the required degree of flexibility. As a result double cardan universal joints were selected. Since universal joints should not be used to transmit thrust from the propeller, a thrust bearing was required. A tapered roller bearing was mounted on a stiffened beam, in turn supported on vibration isolation mounts to attenuate vibration from the engine and from the propeller, especially at the blade rate frequency.

ACOUSTICAL EVALUATIONS

The inclined mounting system was evaluated by comparing noise levels at designated measurement locations. One-third octave band results are presented in figures 11-24 which also include A-weighted (A) sound level results and flat (F) unweighted levels. Figs. 11 and 12 show that in the forward cabin A-weighted sound levels were reduced from an average of 86.5 dB to 74.5 dB with reductions in nearly all one-third octave bands except at low frequencies associated with propeller shaft rotational and blade rate (69 Hz at an engine speed of 2100 RPM). These results were obtained with all of the acoustical blankets installed; the sole variable was the vibration isolation of the engine.

Vibration levels measured on the interior surfaces of the forward cabin are given in Figs. 13 through 16. It is seen that the levels were appreciably reduced by the use of the inclined mounts, especially in the region from 315 Hz through 3.15 KHz. An average reduction of 24 dB was observed in the prominent 1 KHz band. The reduction at 1 KHz on the forward bulkhead was 19 dB, close to the average 16 dB reduction in sound level in the forward cabin. With the engine on inclined mounts the vibration of the forward cabin surfaces was highest on the bulkhead at 1 KHz. The vibration levels on the bulkhead as well as airborne sound in the forward cabin increased when the acoustical blankets were removed. This relationship indicates that the cabin sound is now dominated by airborne sound transmission through the bulkhead.

Sound levels measured at two locations in the aft cabin are presented in Figs. 17 and 18. A-weighted levels averaged 88 dB with the engine hard mounted and were reduced to an average of 85.5 dB after the installation of the inclined mounting system. The reduction occurred mainly in the mid-frequency range. Figs. 19 through 22 present the vibration levels measured on the surfaces of the aft cabin. The small reduction in vibration levels coincided generally with the small decrease in sound level. Fig. 22 shows an apparent resonant condition in the seat panel occurring at the propeller blade rate of 69 Hz. Vibration levels measured on the aft bulkhead with the inclined mounts were on average 10 dB higher than measured on the forward bulkhead over the range of frequencies from 315 Hz to 8 KHz. It later was found that a plywood panel could have caused a sound short allowing engine vibration to be transmitted to the bulkhead. The noise levels with the sound short eliminated will be measured during upcoming trials.

The highest vibration levels were measured on the hull bottom a few inches aft of the plane of the propeller and near the point of attachment of the intermediate strut, Figs. 23 and 24. No significant reduction was observed at the aft location; at the intermediate strut the vibration levels were reduced an average 6 dB in the mid-frequency range.

A General Radio type 1562-B Sound Survey Meter was used to evaluate the A-weighted sound levels at the standard measurement locations. Table 1 lists the sound levels that were measured during various stages of acoustical treatment. As previously reported, when the engine was hard mounted there was no significant difference in cabin sound levels with or without the acoustical blankets around the engine even though engine compartment levels were changed appreciably. When the engine was soft mounted the forward cabin was 12 dB quieter whereas the aft cabin was only 1-4 dB quieter. When the engine was soft mounted the sound levels in the forward cabin increased as the acoustical blankets were removed; in the aft cabin no significant change was measured at 2100 RPM. At slower speeds the levels in both cabins were found to be related to the acoustical treatment of the bulkheads and engine. These observations point to propeller noise as dominating the sound in the aft cabin at 2100 RPM.

SUMMARY

The noise levels measured on the test craft support the conclusion that installing a diesel engine on a properly designed focal point mounting system can result in a substantial reduction in the transmission of engine vibration. In the investigation discussed herein the sound levels in the boat cabins were originally dominated by vibration from the hard mounted engine. When installed on a soft focal point mounting system the vibration was reduced to the point that airborne transmitted sound through the engine compartment bulkheads dominated in the forward cabin while propeller induced noise dominated the aft cabin.

In this investigation, the engine was carried on a mounting cradle which complicated the design of the mounting system and added 128 lb. More recent design studies indicate that the cradle can be eliminated by positioning the mounts directly outboard of the engine mounting feet locations and by changing the mounting angle. The design can be further simplified by the selection of rubber mounts with a higher spring rate ratio than was used in this initial evaluation. Preliminary designs indicate that a spring rate ratio of 6 would be more practical.

RECOMMENDATION

It is recommended that inclined mounting systems be designed for engines in standard boats and simplified arrangements be tested prior to production to verify the design effectiveness.

Table 1

A-Weighted Sound Levels (dBA) re 20 Micro Pascals.

Engine RPM		Sound		Survey		Location		
		P1	P2	P3	P4	P5	P6	P7
	Engine Hard Mounted, Acoustical Blankets on Engine and Bulkheads							
2100		88	88	83.5	86.5	86	98	100.5
	Engine Hard Mounted, Acoustical Blankets on Bulkheads							
2100		89	88.5	87	87	86.5	110	110
	Engine Soft Mounted, Acoustical Blankets on Engine and Bulkheads							
1500		79	79	74.5	70	72	95	95.5
1800		80	80.5	75	73.5	76	95.5	96.5
2100		87	84	80	74.5	74	97	97.5
1800(Neutral)		73.5	73.5	72	66.5	66	92	93.5
	Engine Soft Mounted, Blankets on Bulkheads							
1500		80.5	81	85.5	74.5	74	-	-
1800		81.5	82	83.5	75	79	-	-
2100		87	84.5	87	78	77.5	-	-
1800(Neutral)		74.5	75.5	83	71	73	-	-
	Engine Soft Mounted, All Blankets Removed							
1500		83	80.5	86	75.5	76.5	-	-
1800		84.5	84	88	77.5	81	-	-
2100		87.5	84.5	87.5	82.5	80.5	-	-
1800(Neutral)		76.5	77	84.5	75	75	-	-

P1 - Aft cabin, boat centerline, aft seat

P2 - Aft cabin, stbd seat

P3 - Above engine compartment, boat centerline, at forward cabin door

P4 - Forward cabin, port seat

P5 - Forward cabin, boat centerline, forward seat

P6 - Engine compartment, outboard of internal engine enclosure, port side

P7 - Engine compartment, outboard of internal engine enclosure, stbd side

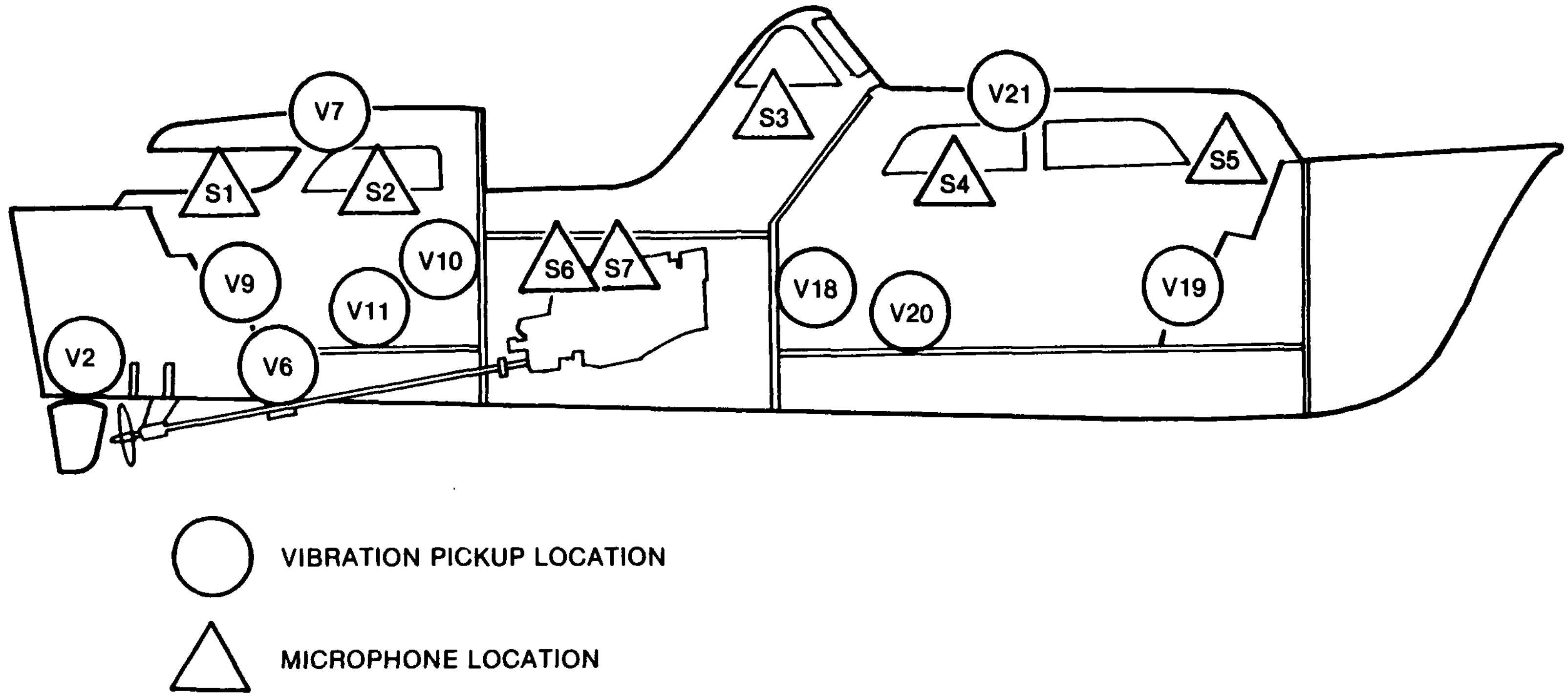

Fig. 1. Profile of test craft.

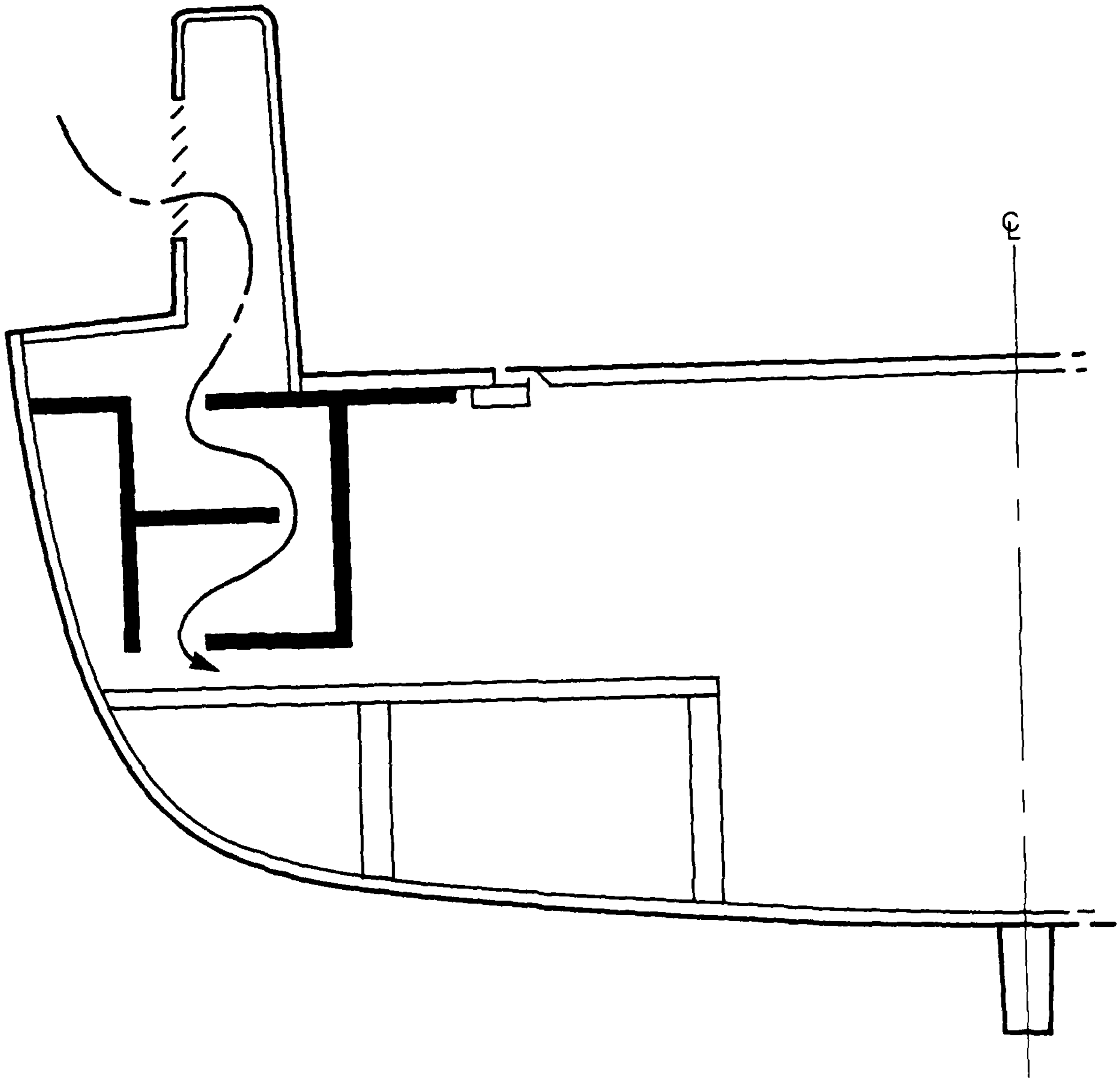

Fig. 2. Baseline modification of engine compartment.

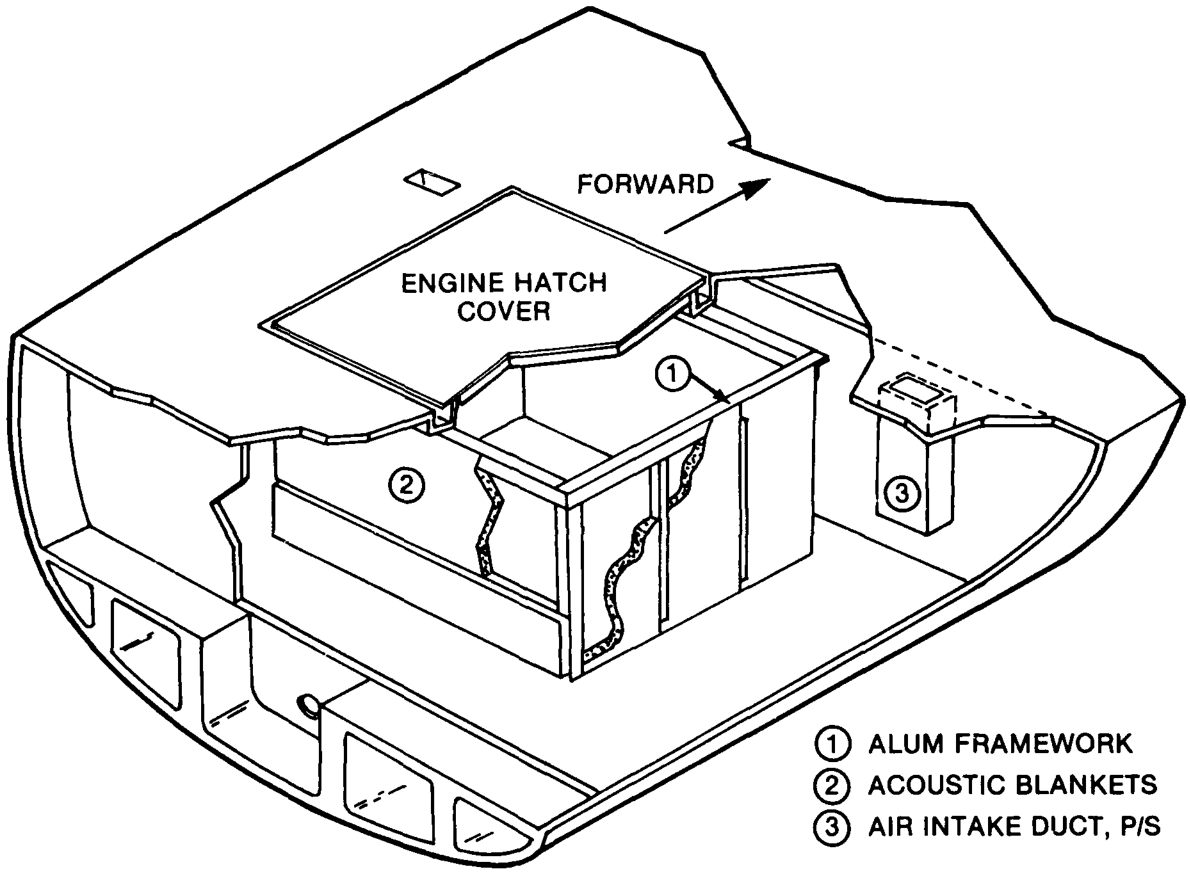

Fig. 3. Close-coupled engine enclosure.

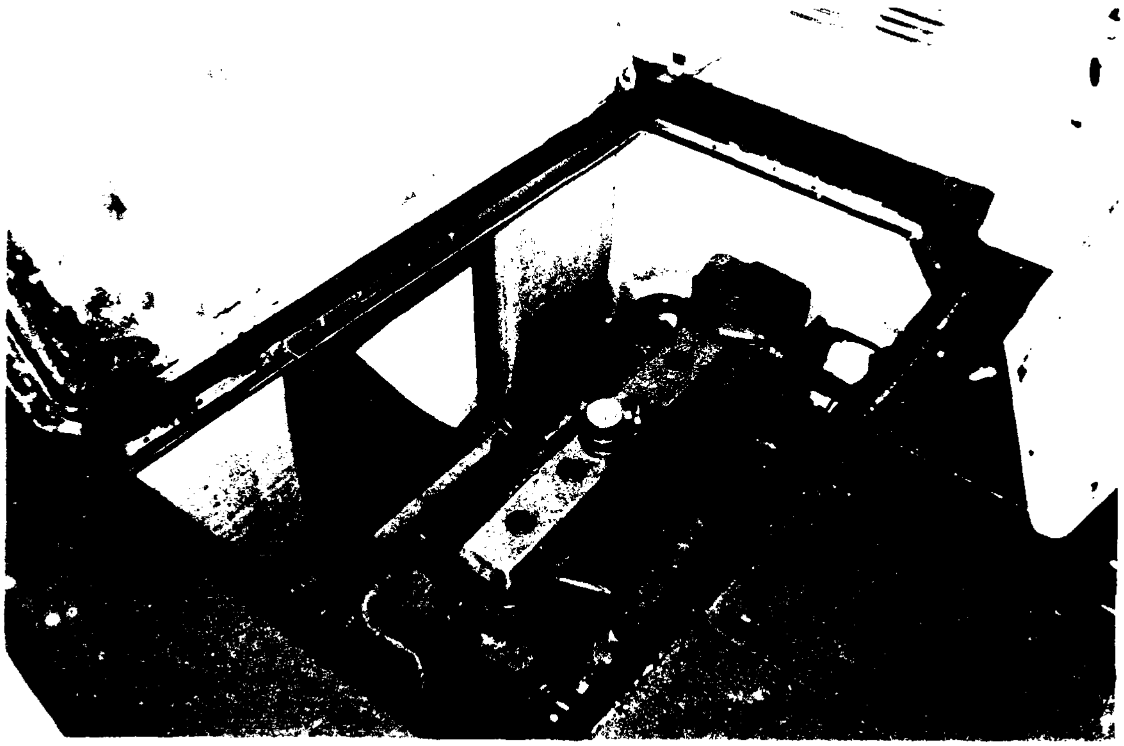

Fig. 4. Engine in close-coupled enclosure.

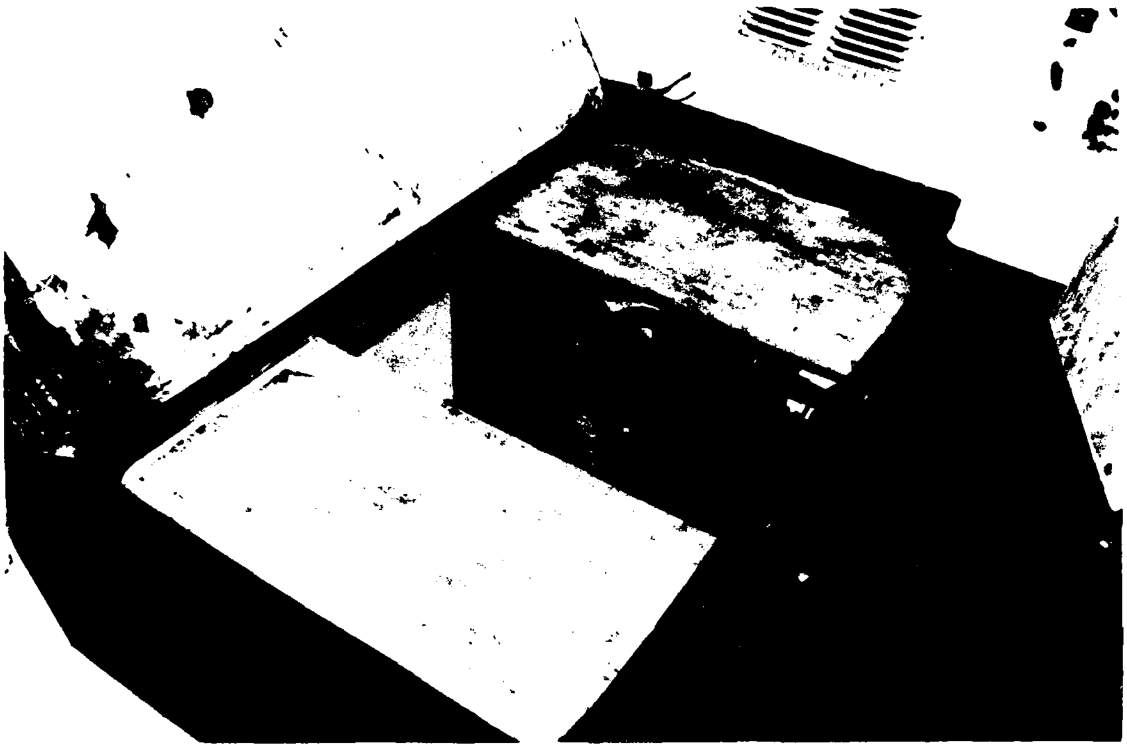

Fig. 5. Secondary hatch covers.

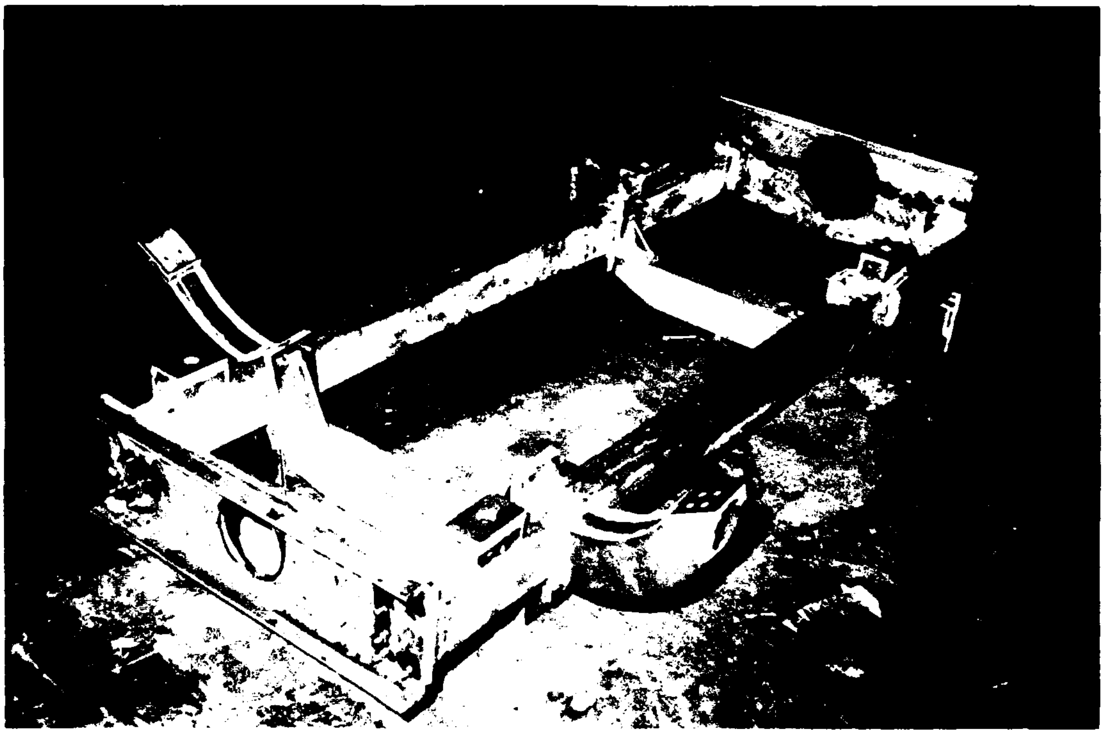

Fig. 6. Engine mounting cradle.

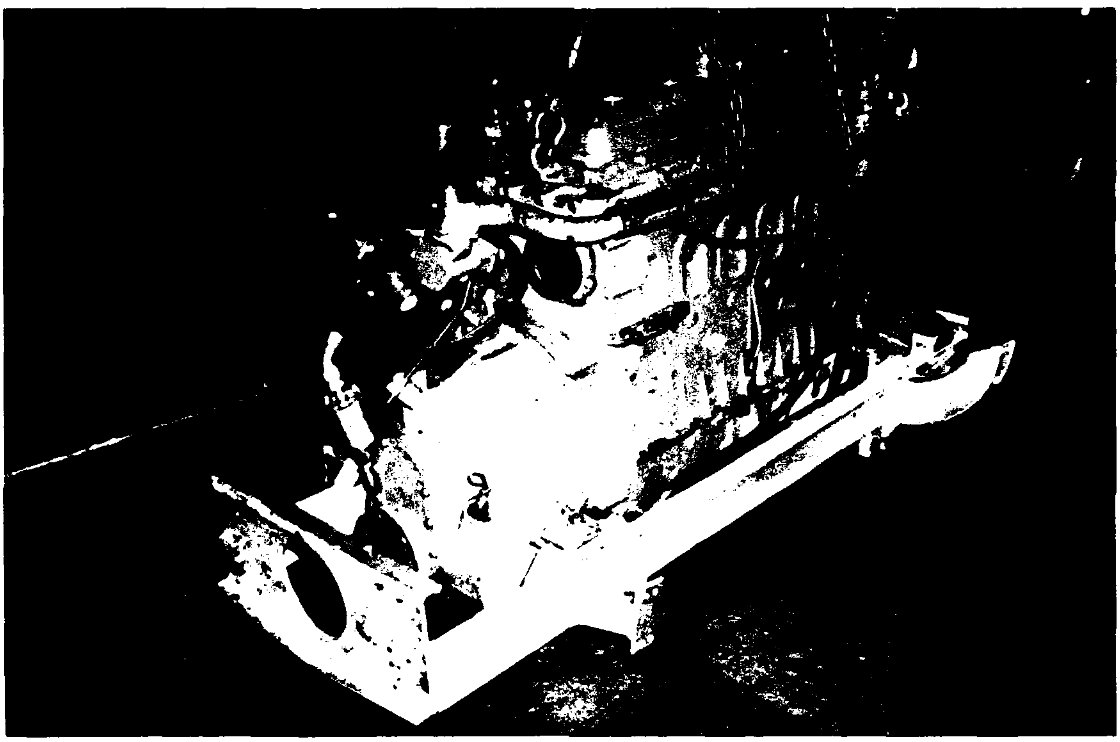

Fig. 7. Engine installed on mounting cradle.

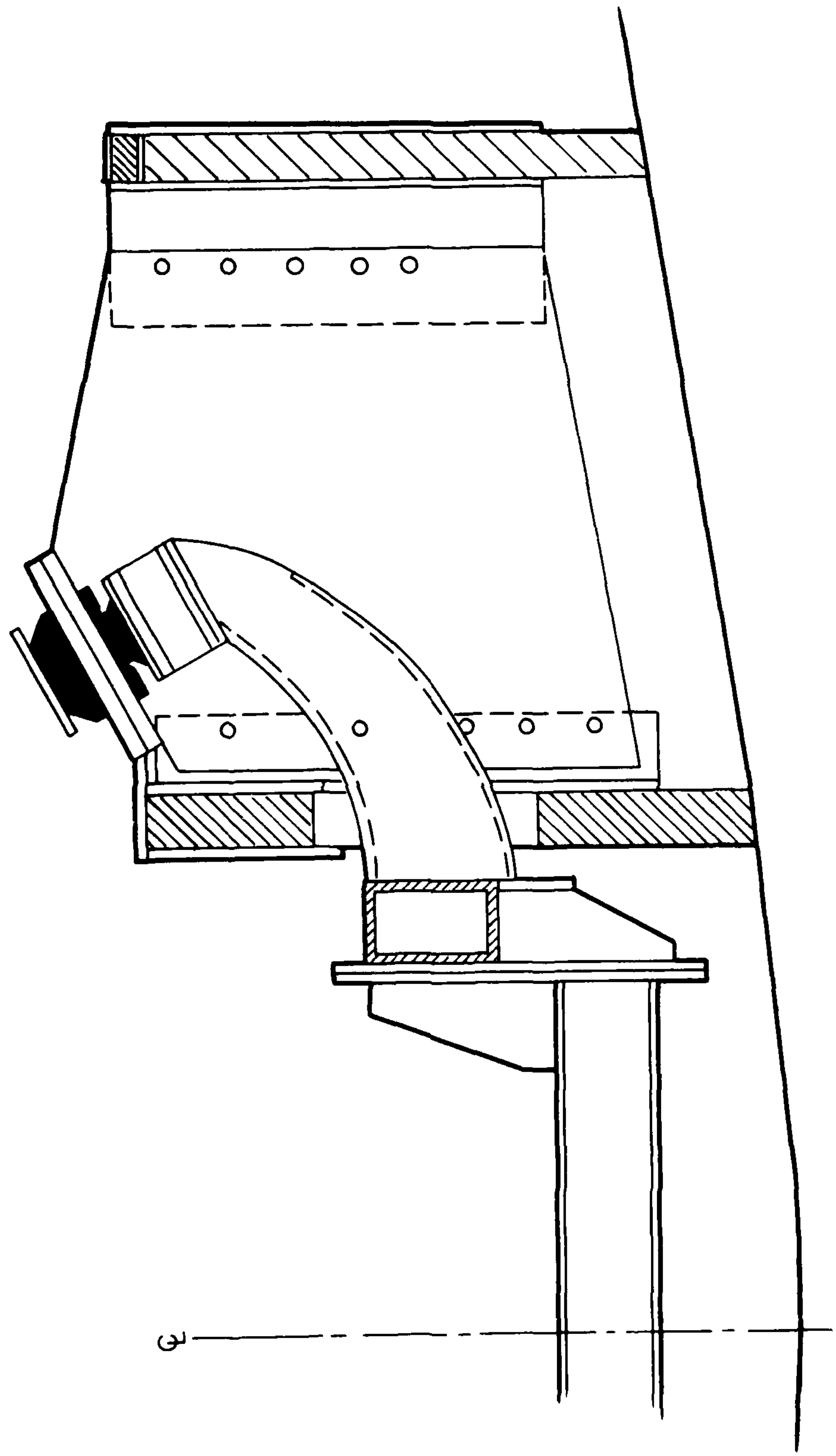

Fig. 8. Section view of forward mount.

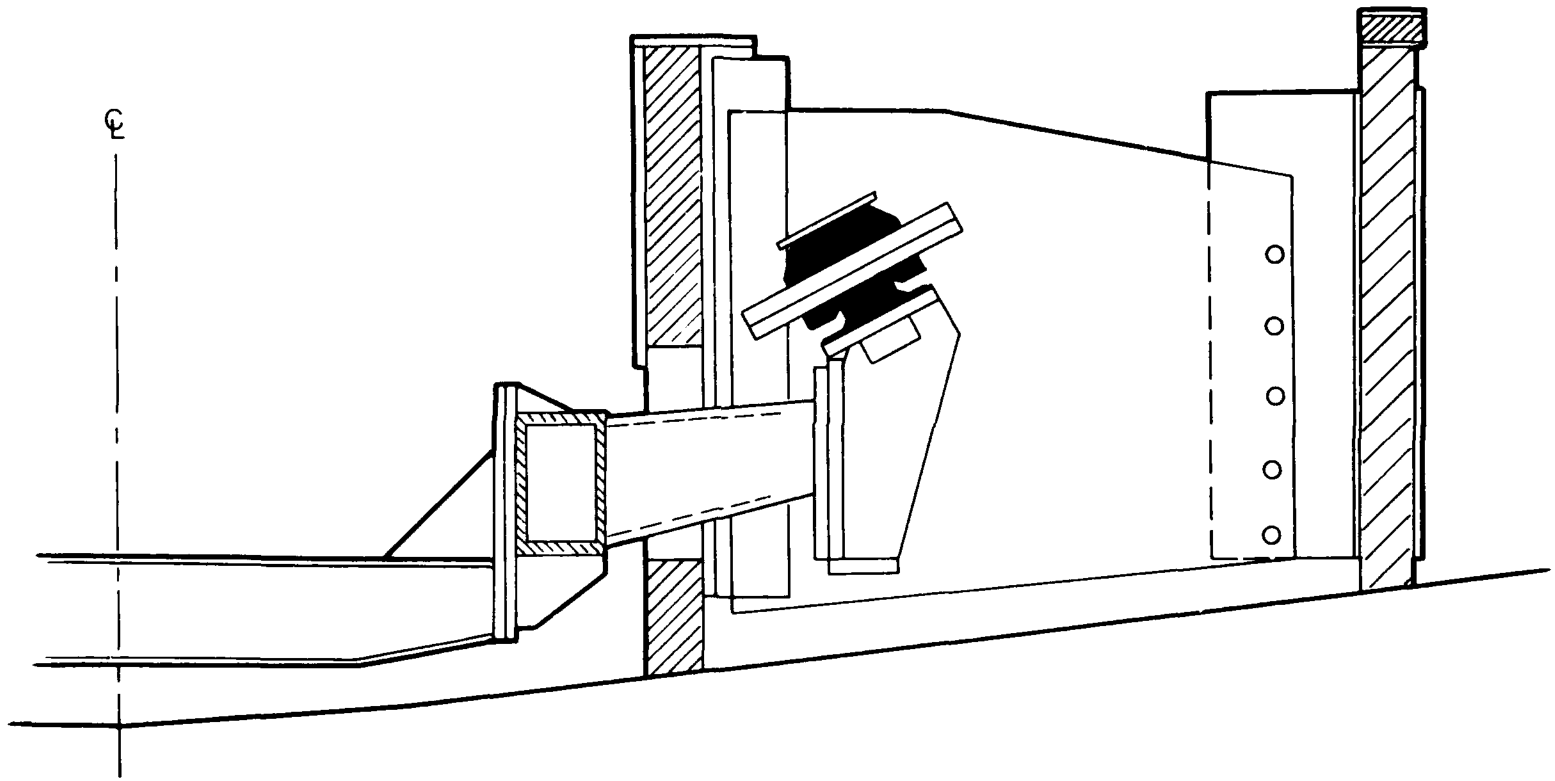

Fig. 9. Section view of aft mount.

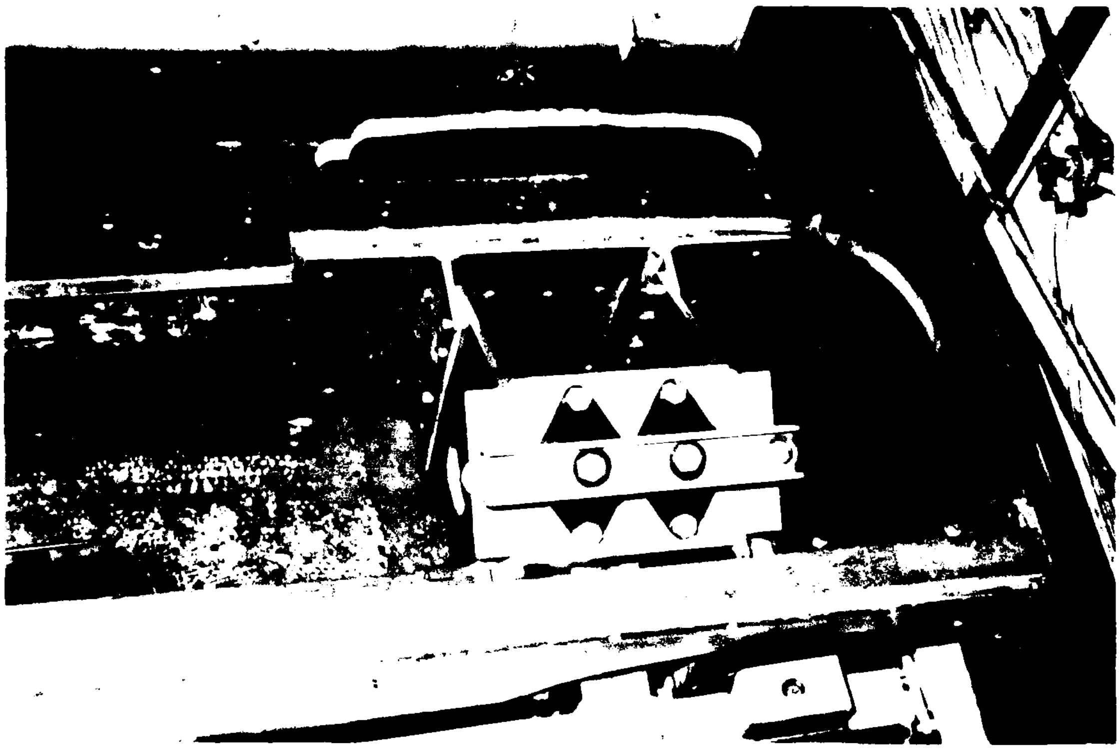

Fig. 10. Forward port mount.

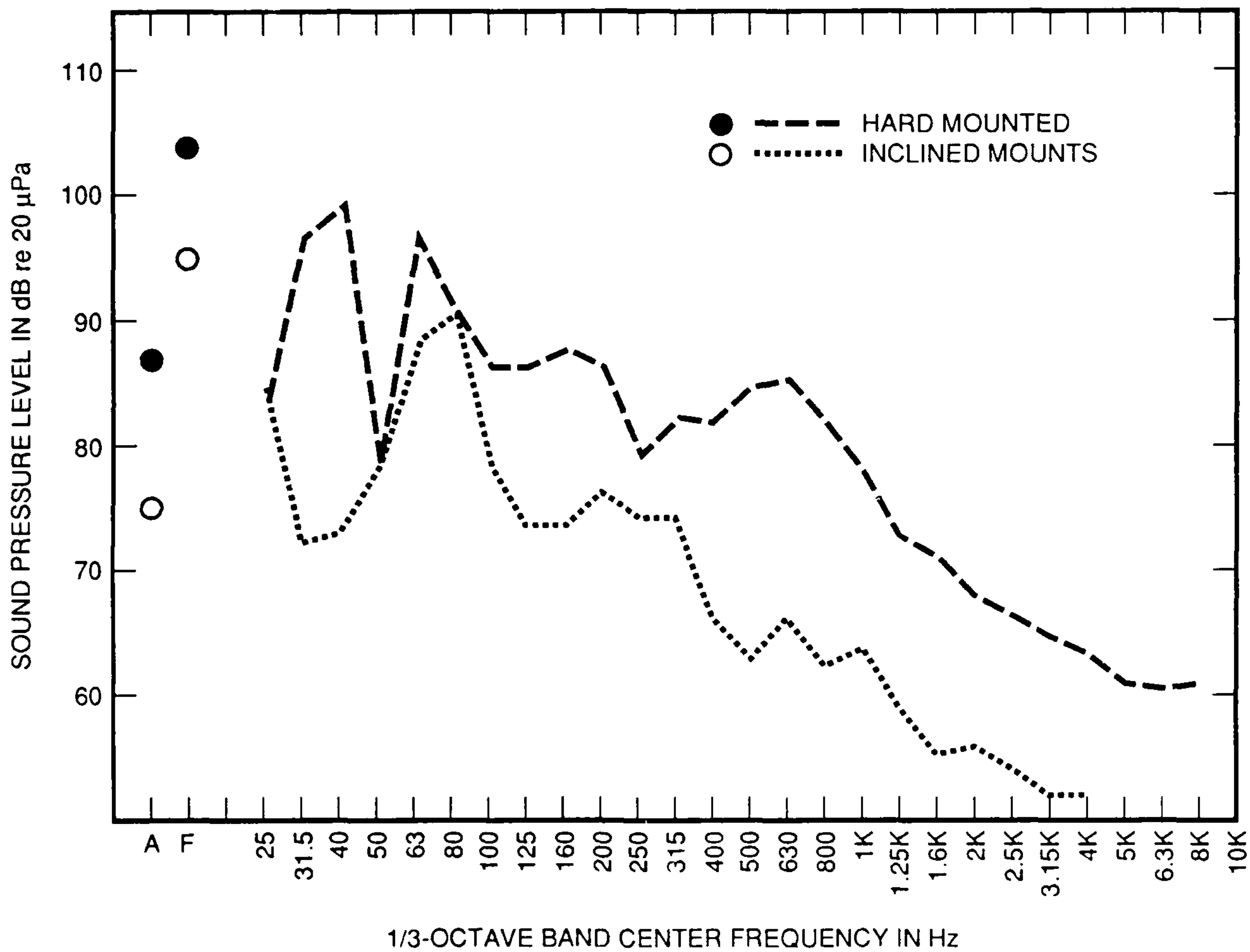

Fig. 11. Sound levels in forward cabin at port seat.

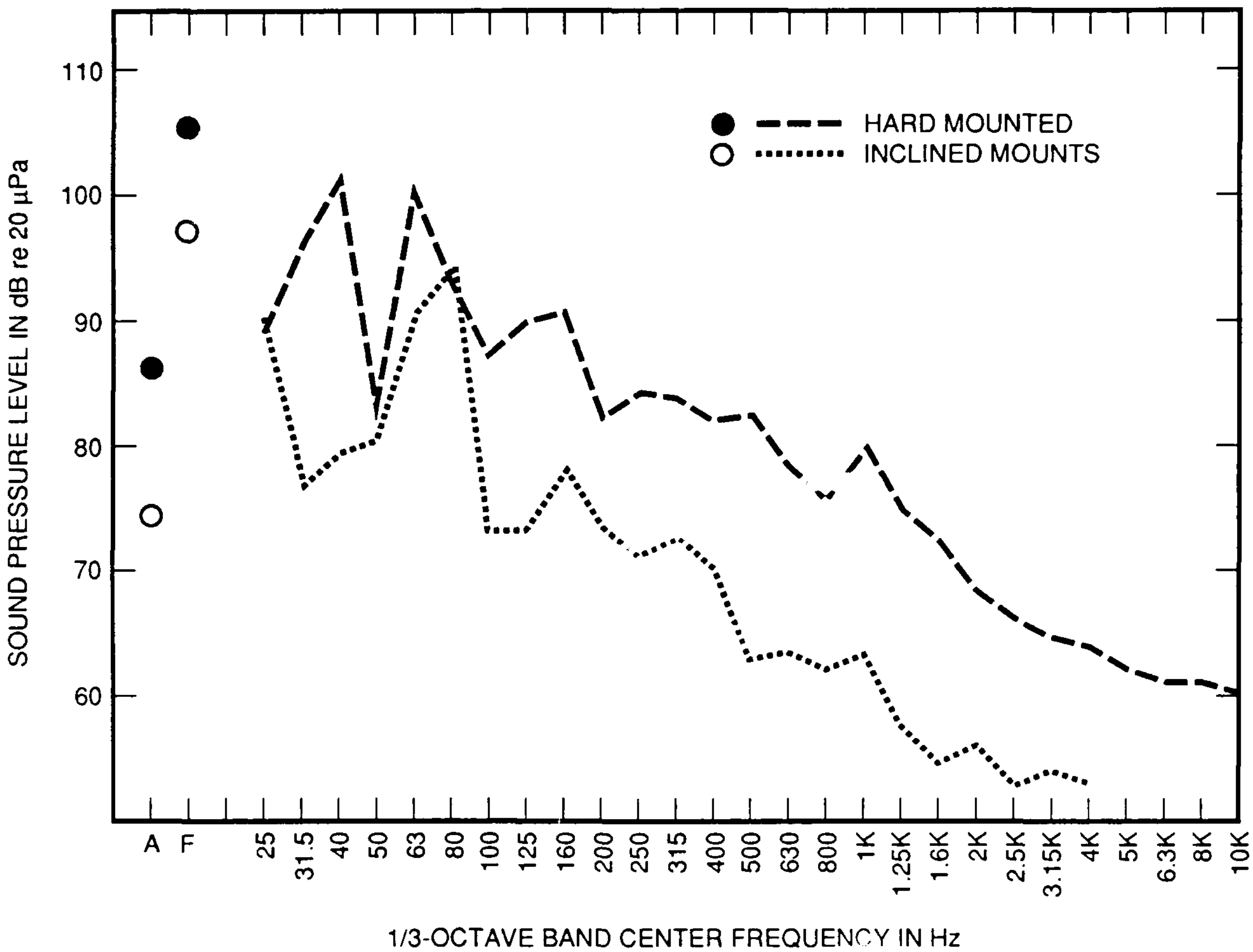

Fig. 12. Sound levels in forward cabin at forward-centerline seat.

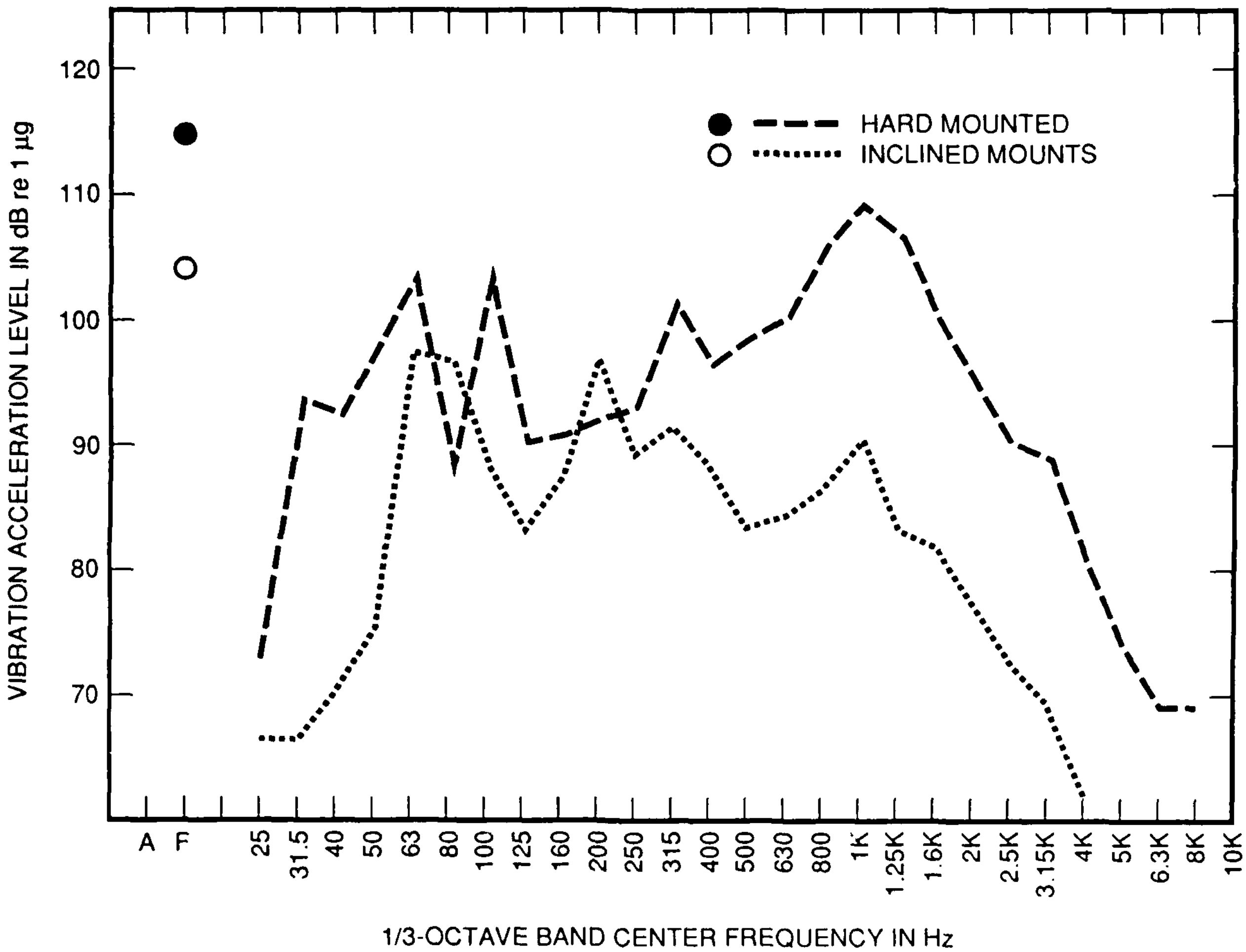

Fig. 13. Vibration levels on forward bulkhead.

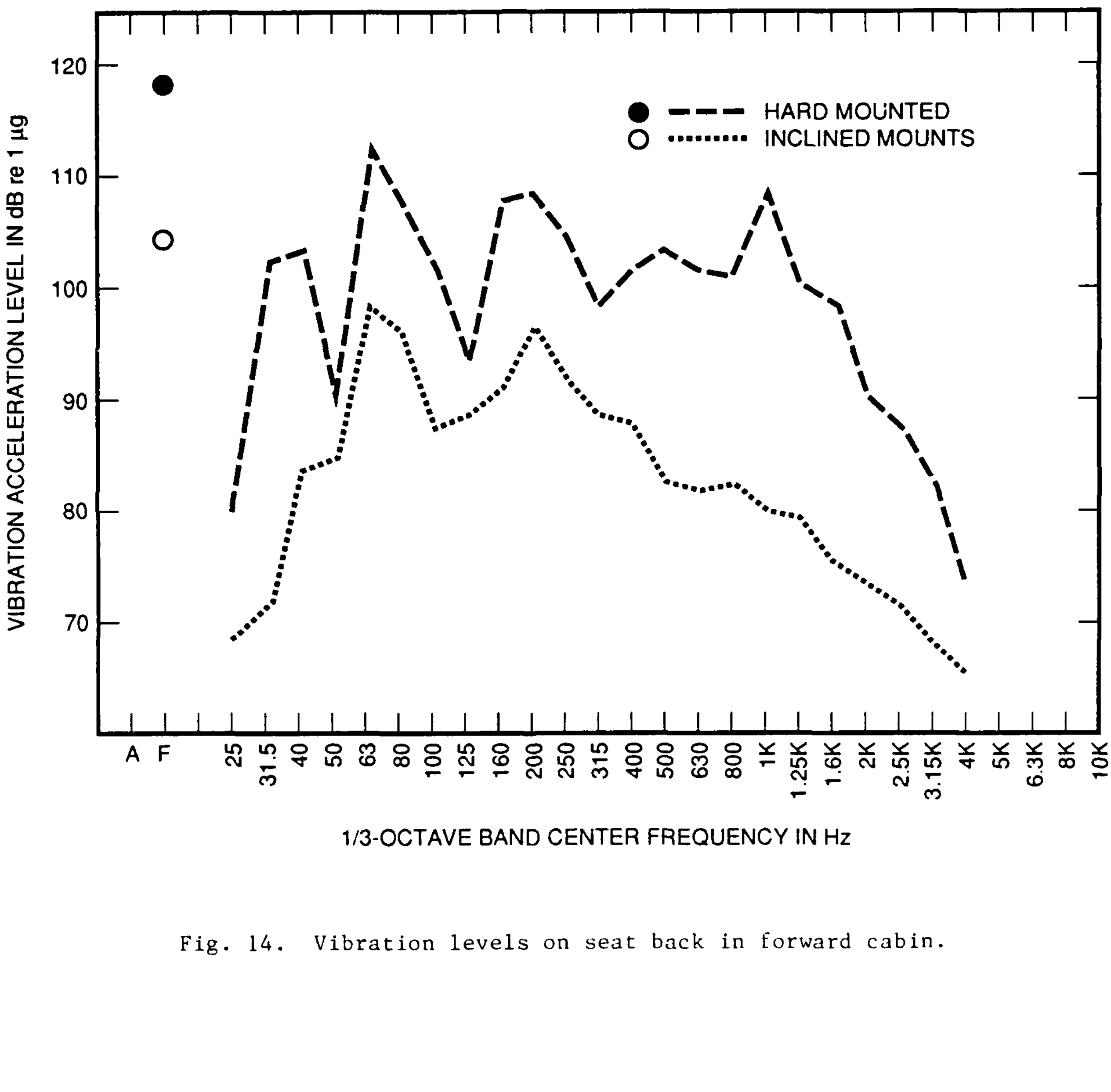

Fig. 14. Vibration levels on seat back in forward cabin.

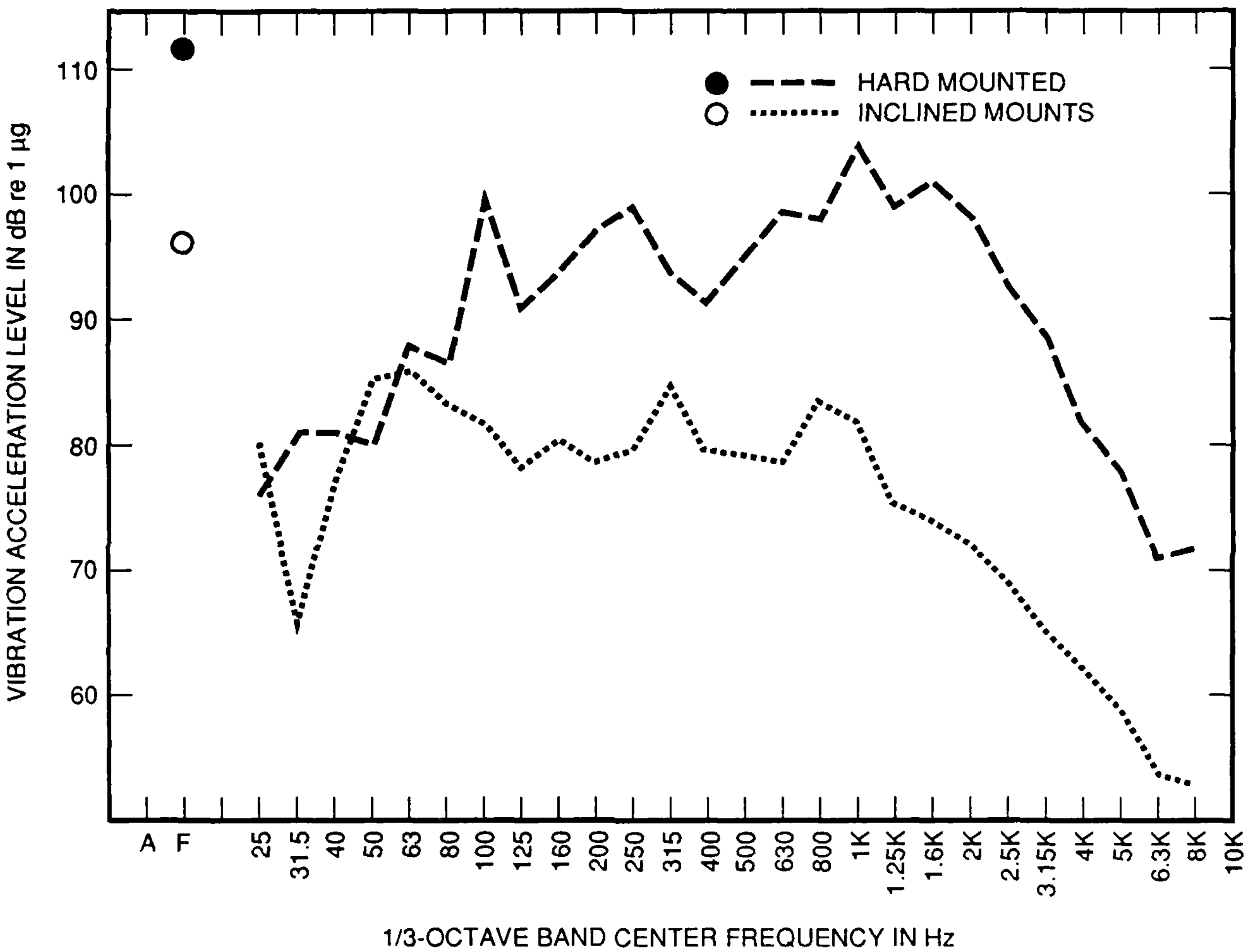

Fig. 15. Vibration levels on walking flat in forward cabin.

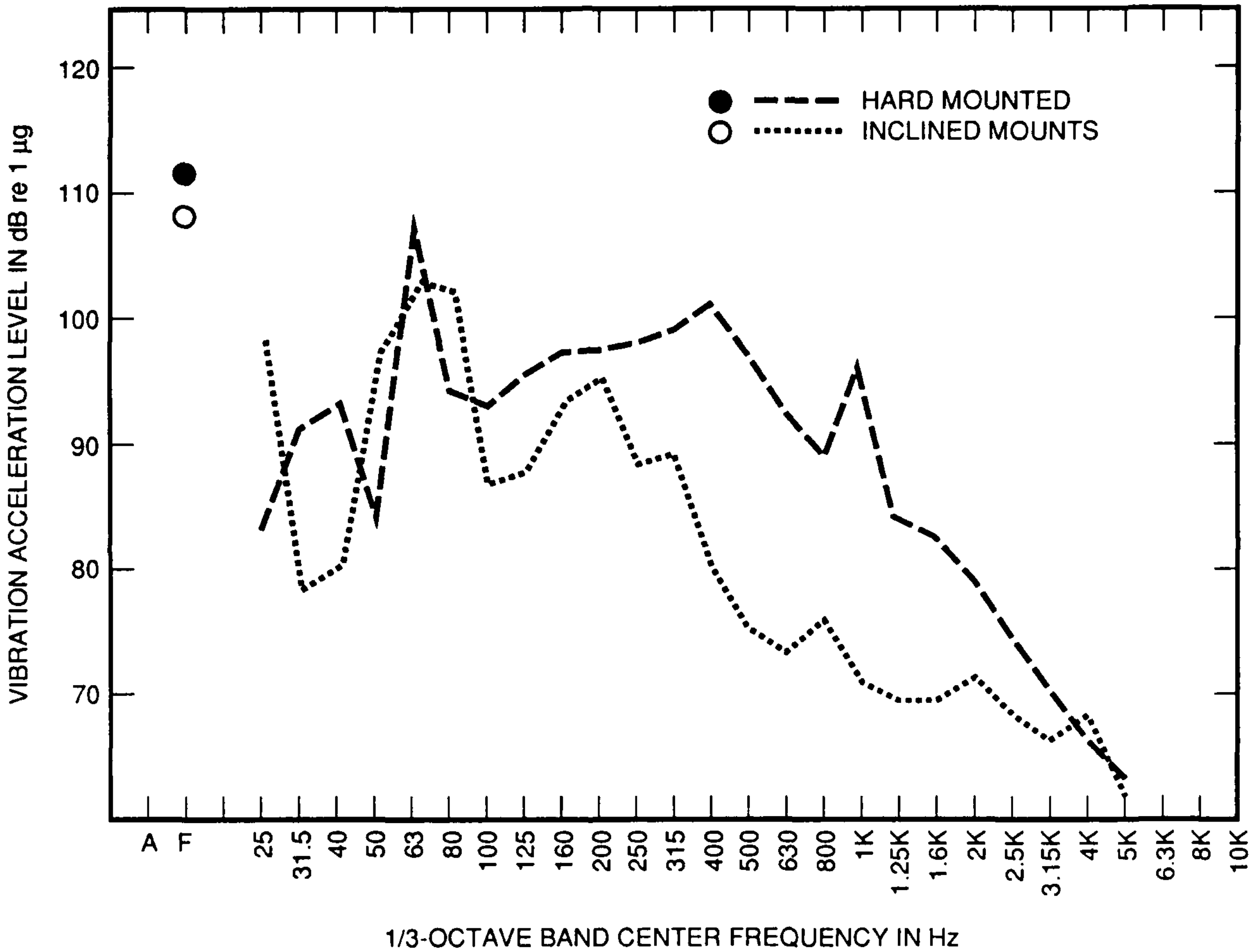

Fig. 16. Vibration levels on overhead in forward cabin.

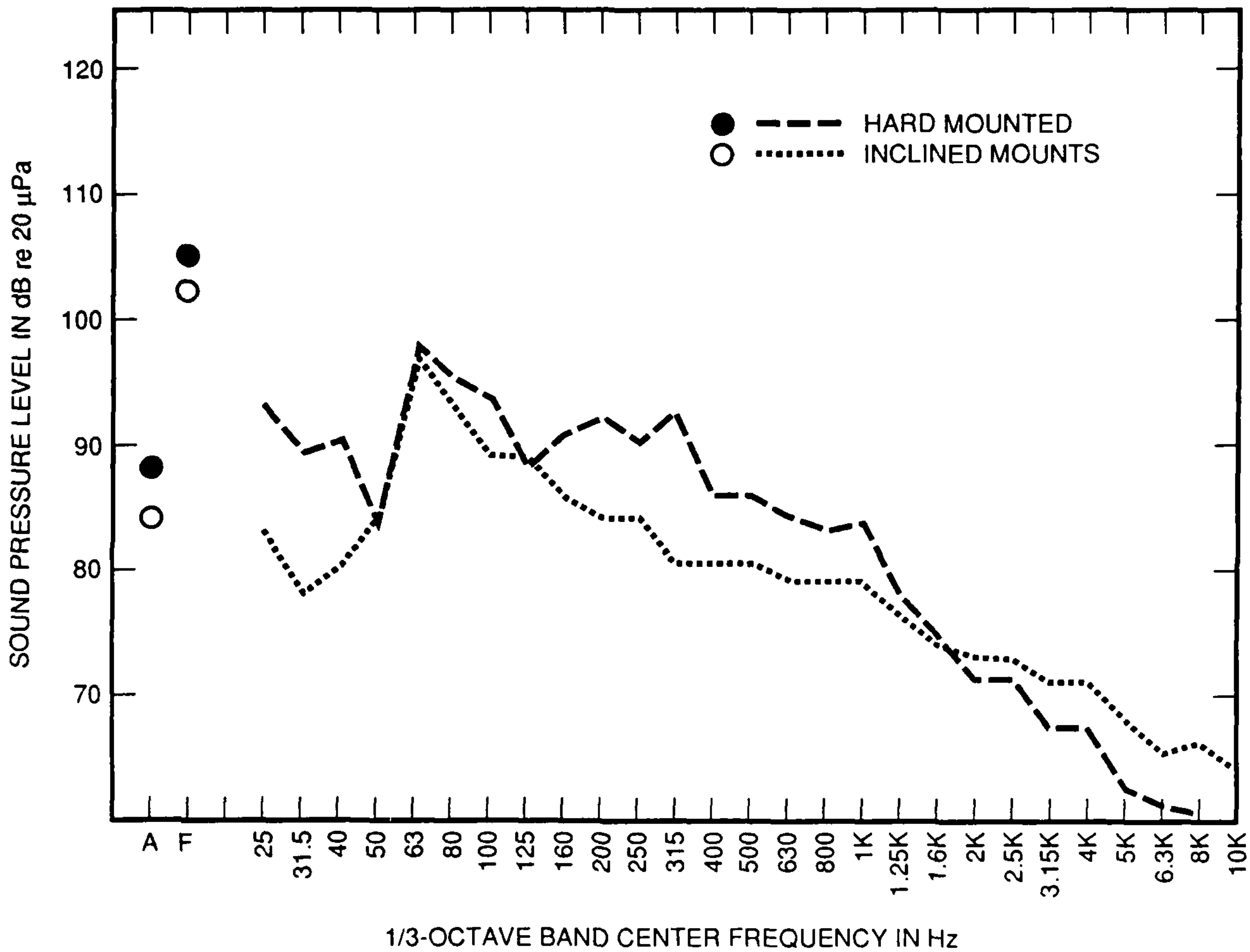

Fig. 17. Sound levels in aft cabin at starboard seat.

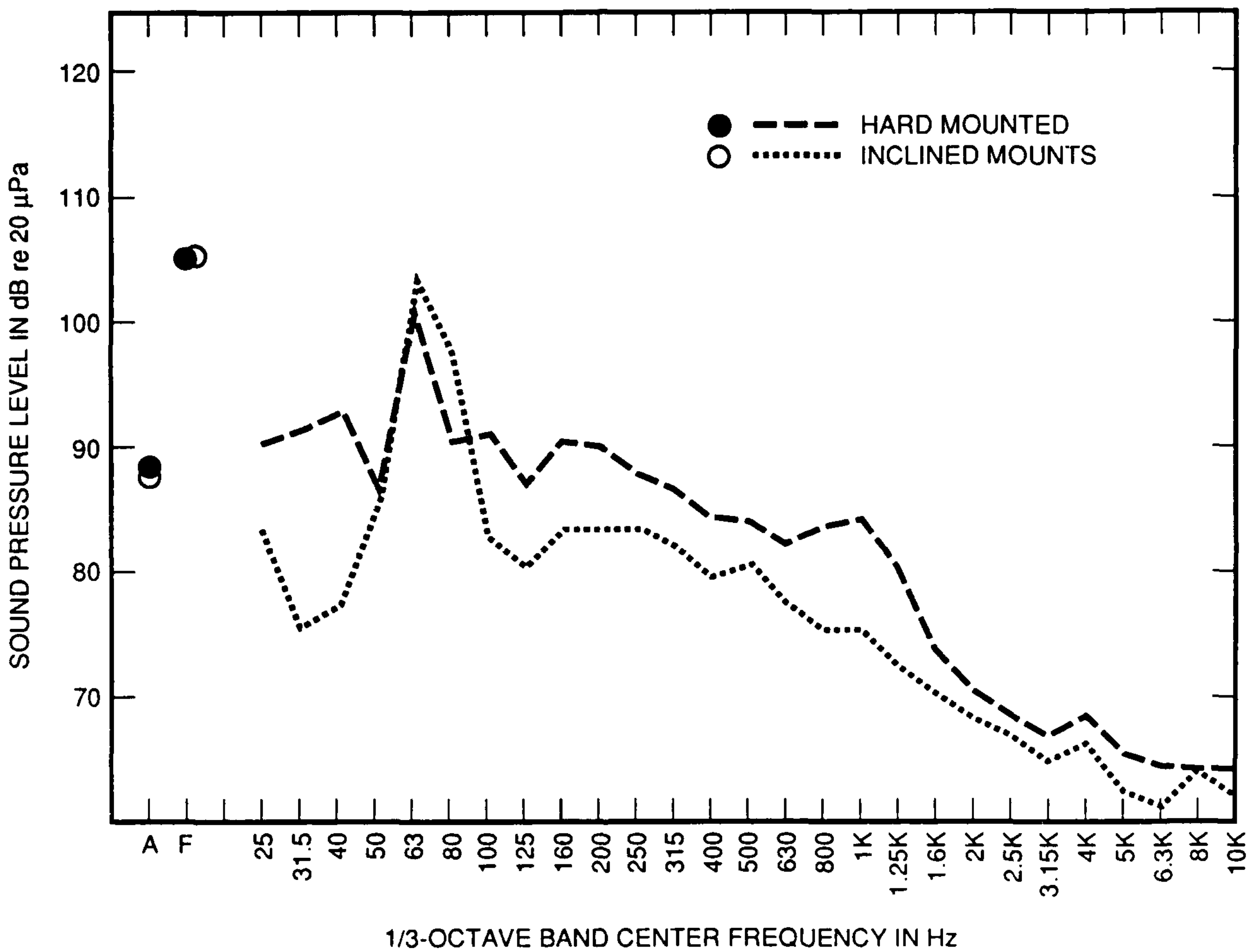

Fig. 18. Sound levels in aft cabin at aft-centerline seat.

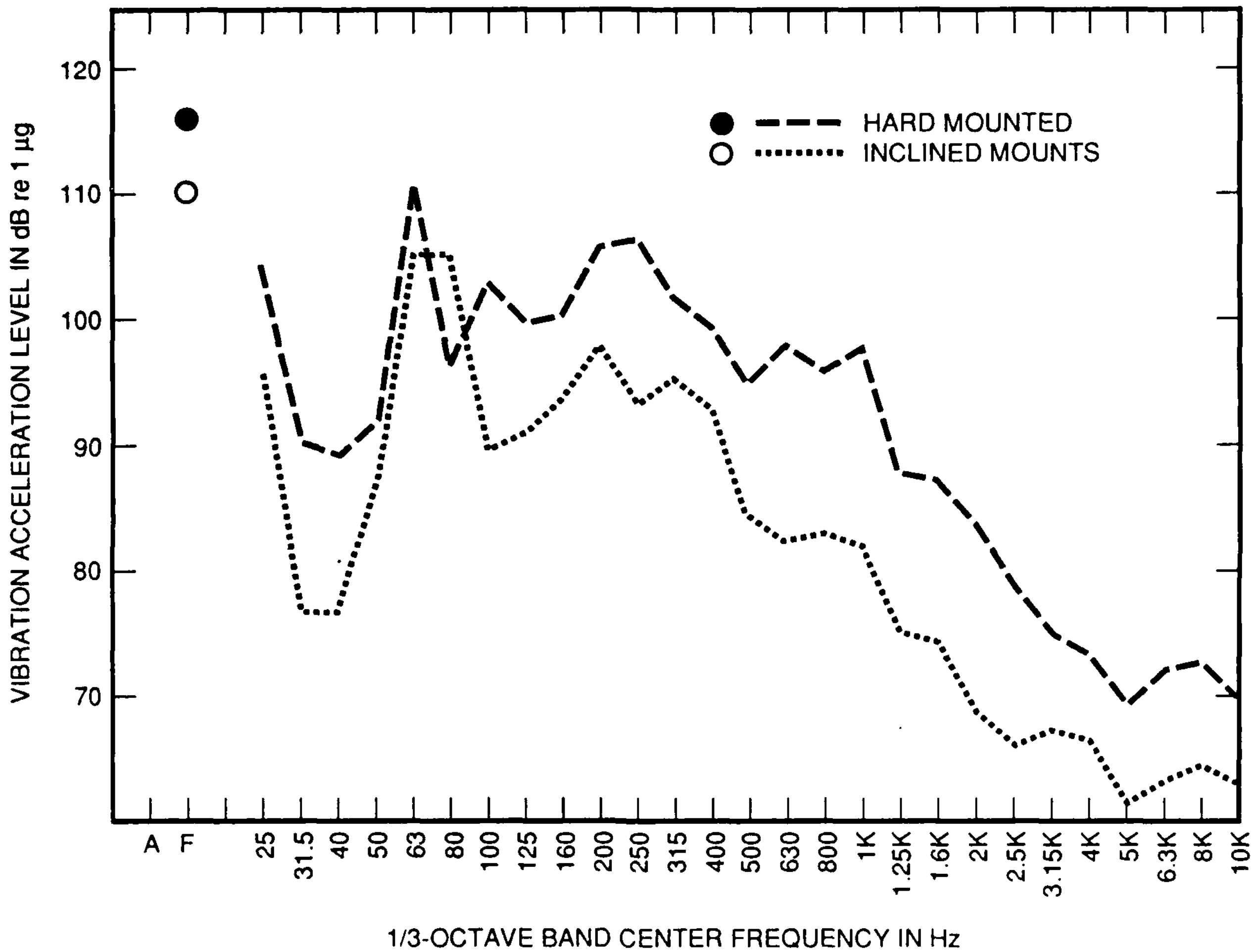

Fig. 19. Vibration levels on overhead in aft cabin.

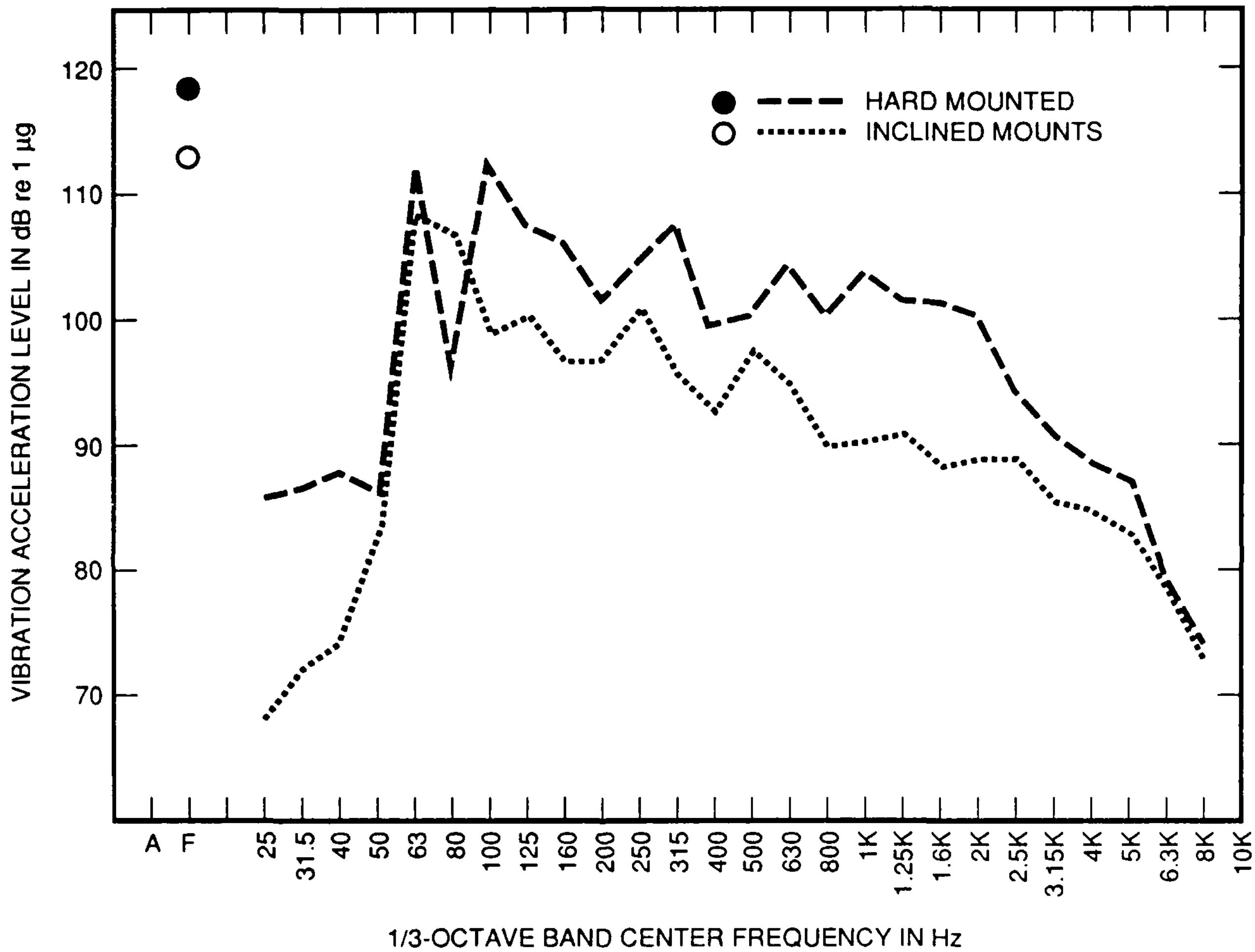

Fig. 20. Vibration levels on walking flat in aft cabin.

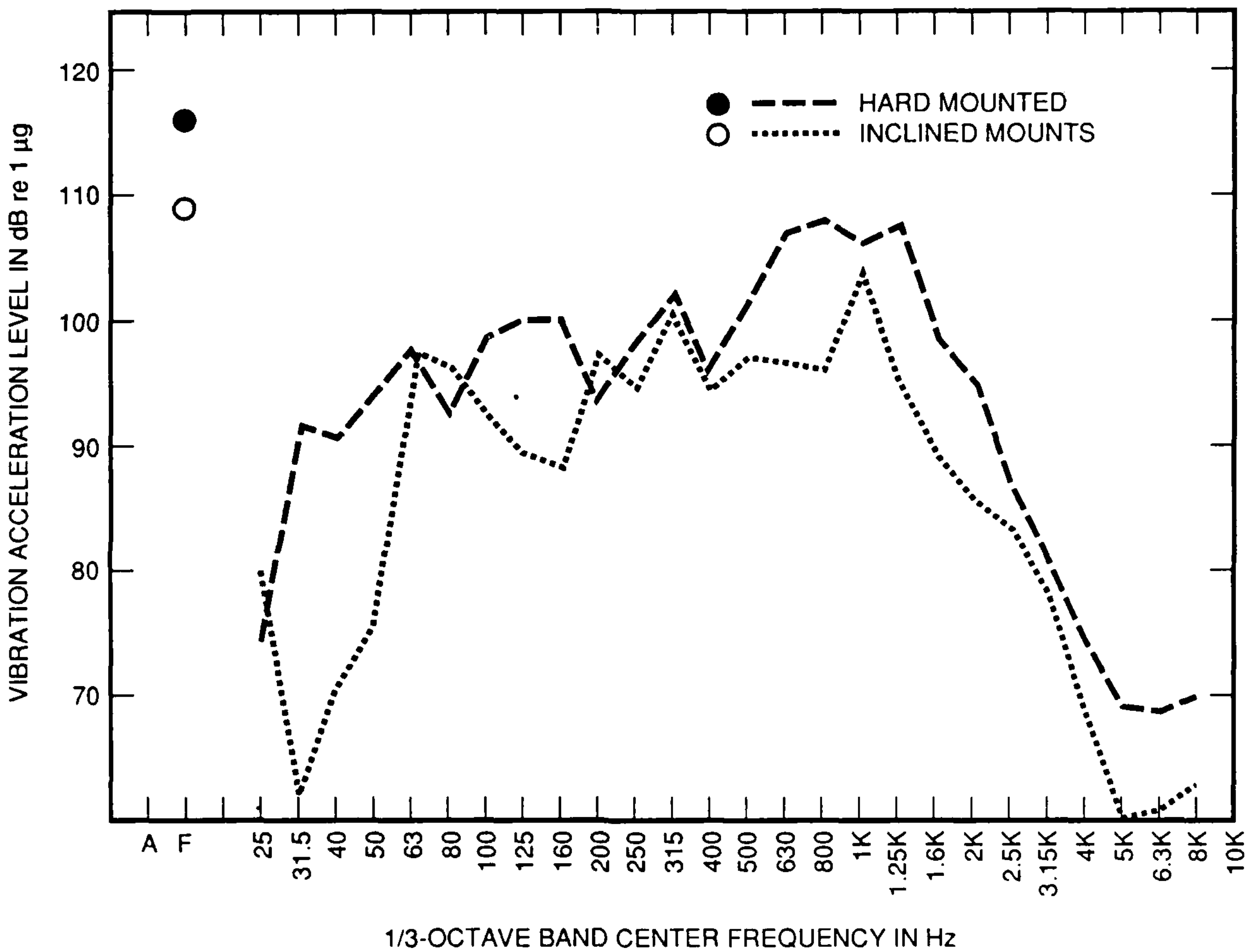

Fig. 21. Vibration levels on bulkhead in aft cabin.

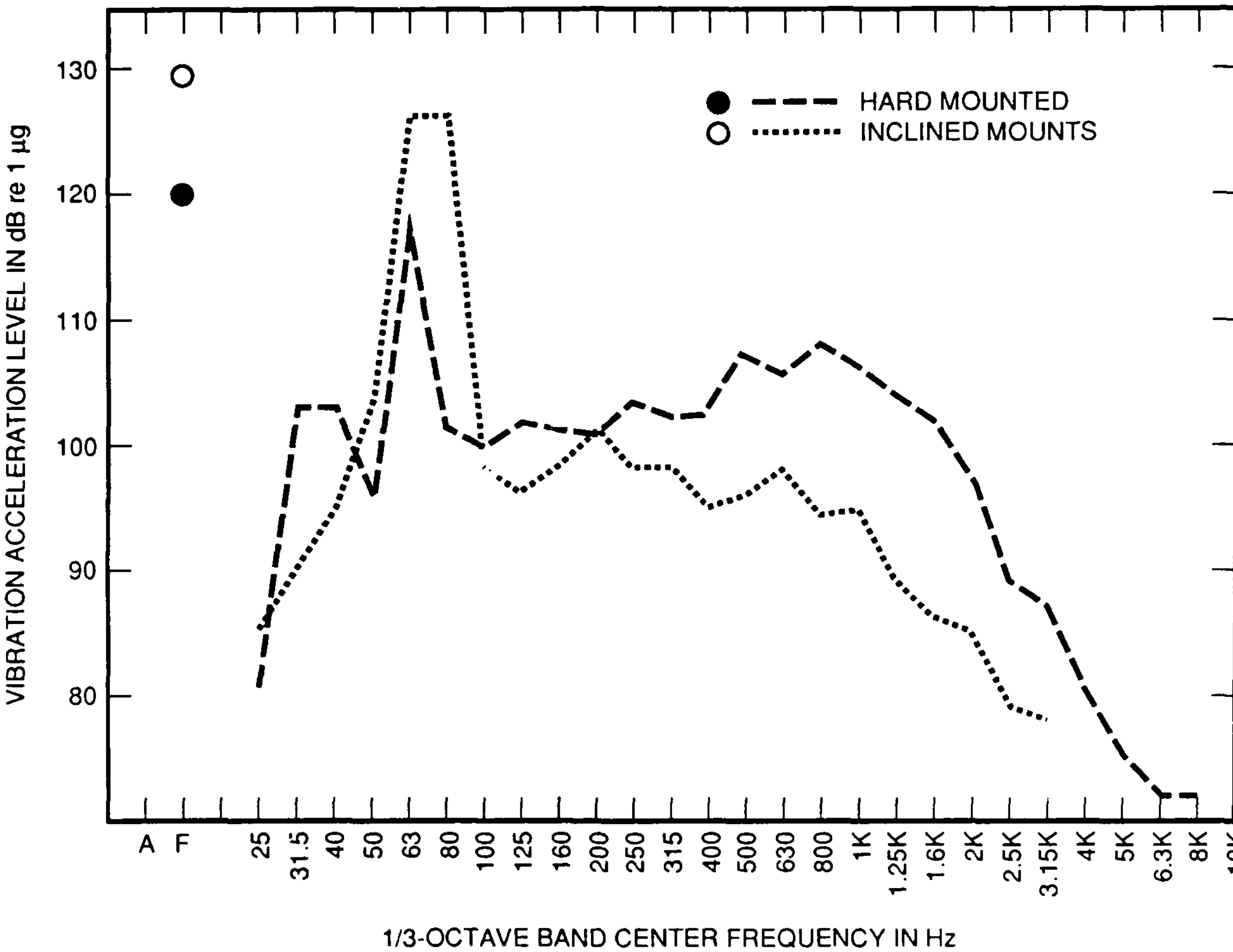

Fig. 22. Vibration levels on seat back in aft cabin.

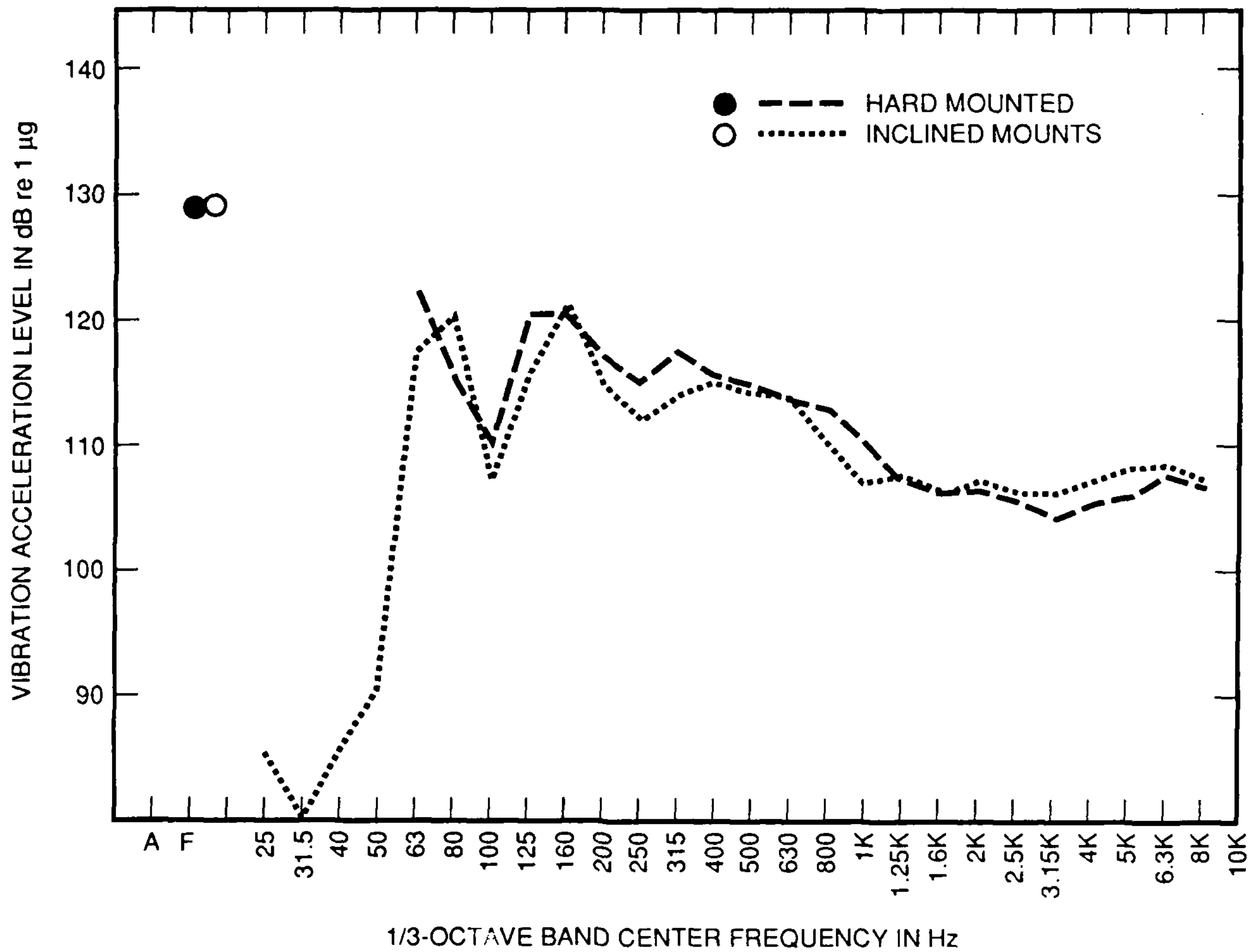

Fig. 23. Vibration levels on hull aft of propeller.

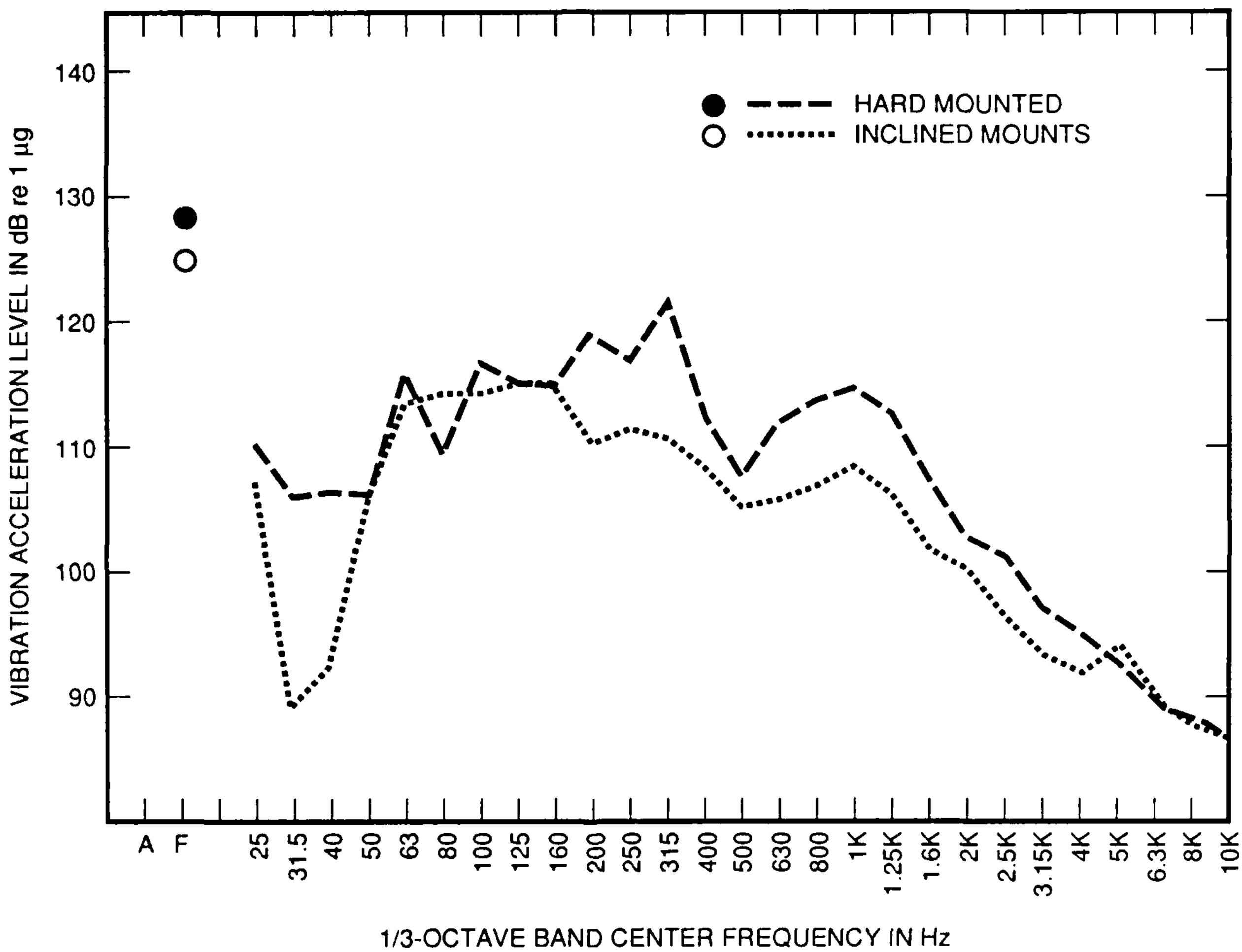

Fig. 24. Vibration levels on hull at intermediate strut.

APPENDIX A

INCLINED MOUNTING SYSTEM DESIGN

FOR TEST CRAFT

The mounting system design begins with a determination of the engine-transmission weight, center of gravity (c.g.) location, and moments of inertia. Referring to Fig. A.1 it is assumed that the axis of minimum inertia or roll axis lies 15 degrees relative to the crankshaft and passes through the c.g. It is seen that the roll axis is relatively high above the forward mounting feet.

Fig. A.2 shows an inclined mounting system. Terms which will be used to determine the proper location of the mounts are indicated. The spring rate of the mount in compression is K_c; in shear is K_s.

The choice of vibration isolation mounts and their location relative to the roll axis is determined in part by using Fig A.3. Mounts must have a higher spring rate in compression than in shear and be rated for the dead load to be carried. These requirements drastically reduced the number of mounts that would be suitable. Standard navy mounts type 6E900 or 7E450 could be used since the spring rate ratio is approximately 2.5. Type 7E450 mounts were selected because they are lighter and would be more effective for a given termination impedance. A pair of the mounts were to be used at four corners.

An examination of Fig. A.3 reveals that for any spring rate ratio there is a mounting angle that results in a maximum value of a/b. For the type 7E450 mounts the spring rate ratio of 2.5 yields a maximum value for a/b of 0.47 with a mounting angle of 30 degrees.

It is desirable to locate the mounts close to the engine since the effectiveness of the mounts improves at locations closer to the roll axis. This essentially dictates locating the mounts relatively high at the front of the engine. Using these procedures it was decided to locate the front mounts 20-in. outboard of the engine centerline and 9.4-in. below the roll axis.

The next decision to make was the longitudinal location of the mounts. This was performed by a computer analysis of the six degrees of freedom of the mass-elastic system for various mount locations. Ultimately it was decided to locate the mounts 23 in. from the c.g. At this distance the six natural frequencies are at or below 9 Hz. Fig. A.4 shows the computer developed transmissibility curves. With the mounts located farther from the c.g. the natural frequencies were increased which results in less attenuation. X, Y, and Z are the translational modes; β is the pitching mode about a horizontal axis passing transversely through the c.g.; γ is the yaw mode; and α is the roll mode.

With the mounts located 23-in. longitudinally from the c.g. the rear mounts were positioned in the transverse plane passing through the roll axis, resulting in a zero value for 'a'. Fig. A.3 indicates that the mounts should have a zero angle of inclination. However it was decided to incline the aft mounts 30 degrees to balance the mounting loads and to reduce the spring rate in rotation K_α by 28 percent which yields more effective vibration isolation. The spring rate in rotation is defined by the eq.

$$k_\alpha = \frac{2b^2 k_s}{\cos^2(90-\beta) + \frac{k_s}{k_c} \sin^2(90-\beta)} \quad . \tag{1}$$

When the spring rates are given in units of lb/in. and the distance b is in., the spring rate in rotation k_α will be in units of in.-lb/radian. The natural frequency about the roll axis is given by the eq.

$$f_n = \frac{1}{2\pi} \left(\frac{k_\alpha}{I_\alpha} \right)^{1/2} \quad , \tag{2}$$

where f_n = natural frequency, Hz

k_α = torsional spring rate, in.-lb/radian

I_α = moment of inertia about roll axis, in.-lb-sec^2.

It can be seen that the natural frequency is directly related to the mount location dimension b. The natural frequency about the roll axis is of primary interest since the most serious vibration disturbance is the one tending to roll the engine-transmission about its roll axis.

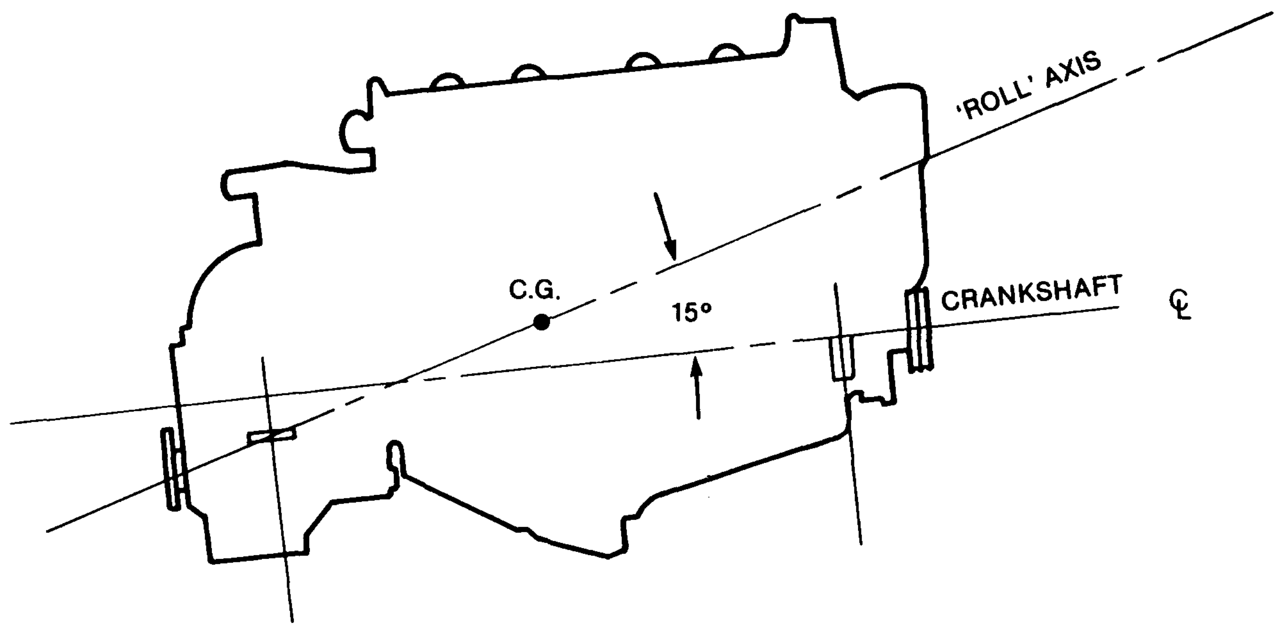

Fig. A.1. Roll axis angle.

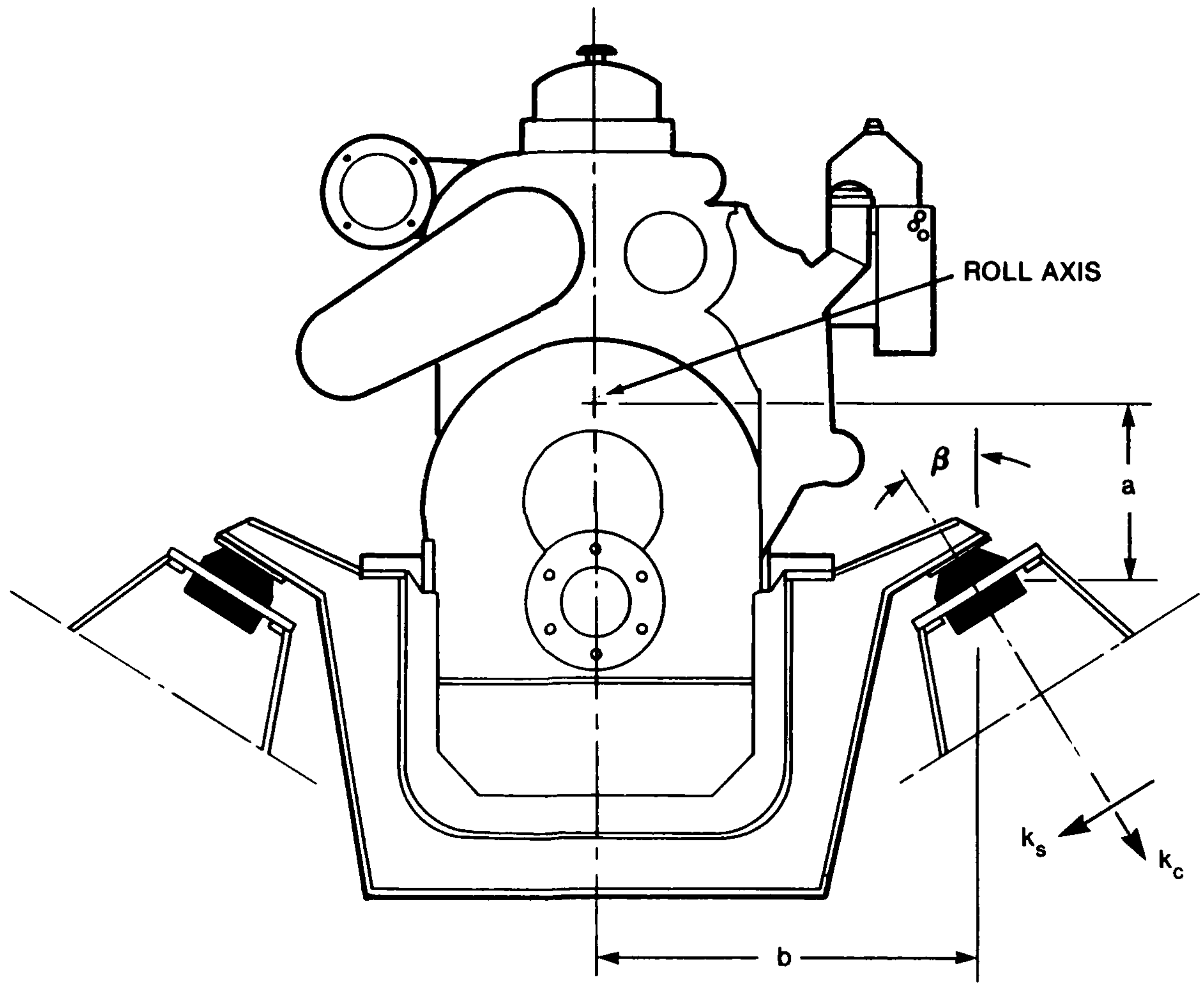

Fig. A.2. Inclined mounting concepts.

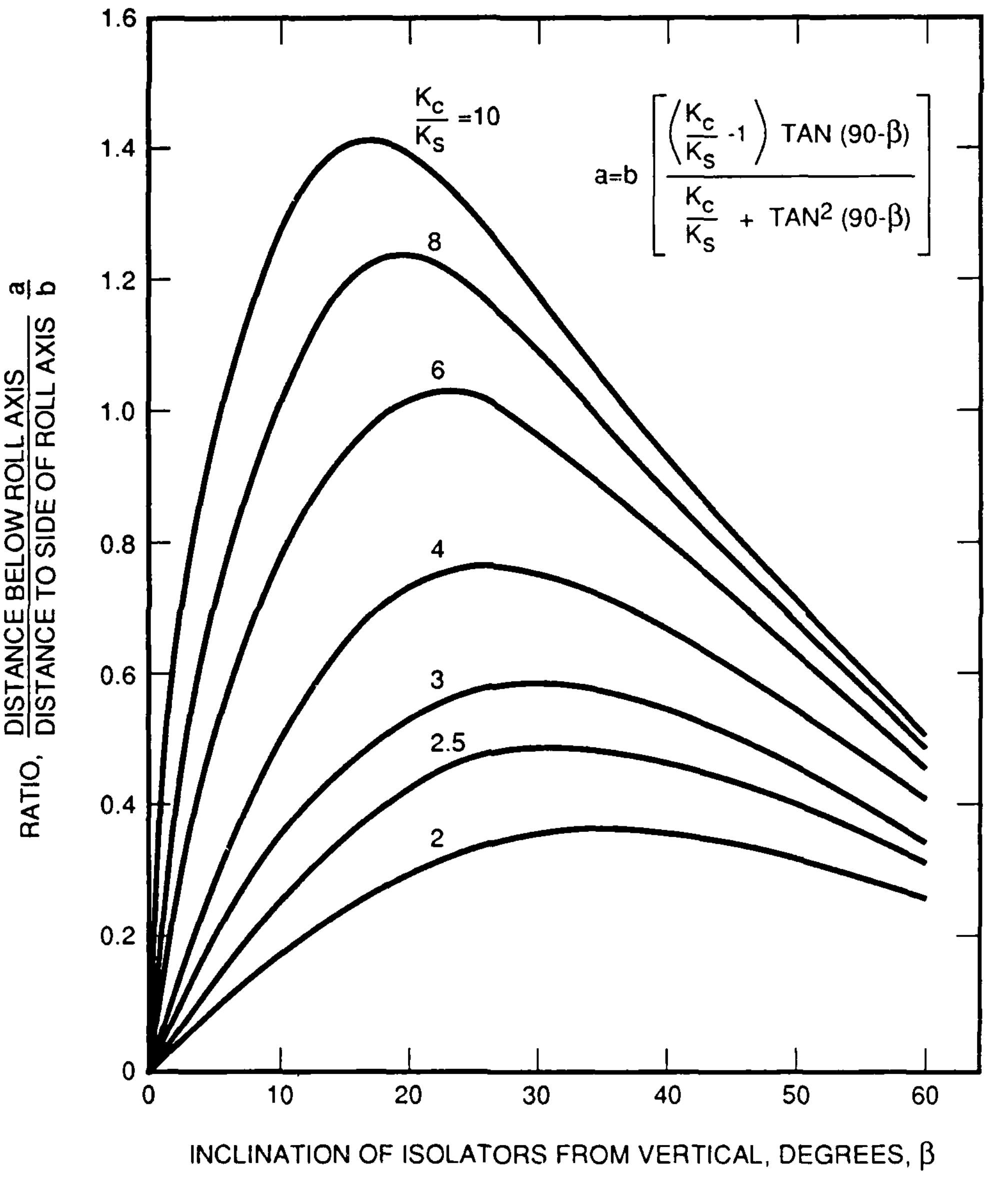

Fig. A.3. Mount design chart.

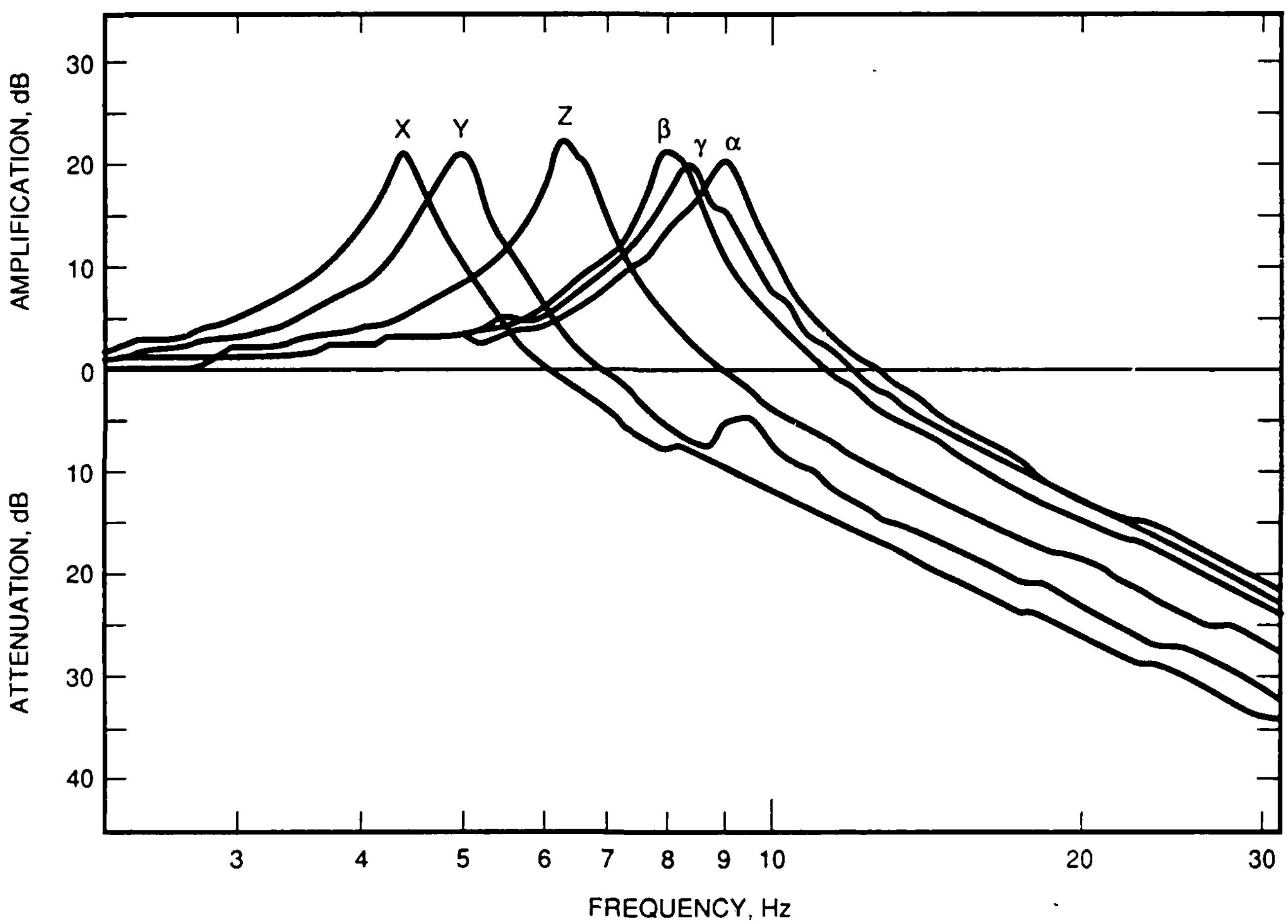

Fig. A.4. Mounting system natural frequencies.

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